INDUSTRY COIL CALIBRATION

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INTRODUCTION

As the LHC machine is in the construction stage and many magnets are being tested for validation, a new system dedicated for coil calibration is required. Moles features must be measured periodically in order to guarantee the precision of the magnetic measurements and to follow their stability. Concretely, some of the operations that must be carried out are the recalculation of the coils surfaces inside the mole, verifying the parallelism between them, checking the linearity of the gravity sensor...

Industry Coil CAlibration (ICCA) system, created to satisfy these requests from AT/MTM, is composed by a program developed in LabVIEW running in Sun Workstations that controls some devices in a mini-rack, dedicated just for calibration purposes, attached to DIMM and QIMM systems. This system is based on magnetic measurements since it is the best and most direct way to verify that the expected field properties (strength, quality and geometry) of the magnets have been reached. It will be useful not only in dedicated benches at CERN but also in the industry.

CHAPTER 1.

CERN

The creation of an European Laboratory was recommended at a UNESCO meeting in Florence in 1950 and, three years later, a Convention was signed by 12 countries of the 'Conseil Européen pour la Recherche Nucléaire'. CERN was born as the prototype of a chain of European institution in space, astronomy and molecular biology. This scientific laboratory sites on both sides of the Franco-Swiss border west of Geneva at the foot of the Jura Mountains.

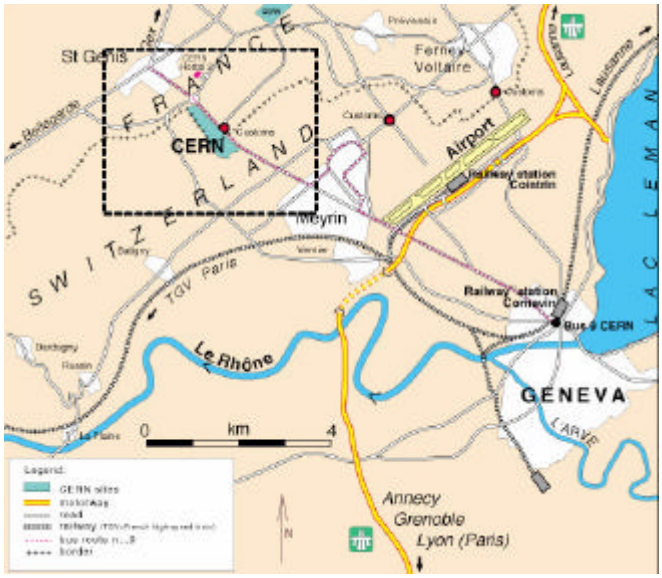


Figure 1.1: CERN's location.

CERN is today composed of 20 member States: Austry, Belgium, Bulgary, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Italy, Netherlands, Norway, Poland, Portugal, Slovak Republic, Spain, Sweden, Switzerland and the United Kingdom and around 6500 scientists use CERN's facilities. [1]

CERN's aim is to provide the European scientific community with the facilities to probe the structure of matter and reach a better understanding of the behaviour of

the universe, how was it created… only for scientific purpose with no immediate technological or commercial objectives. It has been built and operated the particle accelerators needed as means for such research in a unique centre which allows physicists around Europe to collaborate more fruitfully than if each country maintained an independent program. However, even in the short term this fundamental research, with its stringent demands for accuracy and ultra-fast response, pushes modern technology to the limit.

For high interaction energies, the laboratory has developed several fixed targets and colliding beam machines. The first ones were the Proton Synchrotron (PS), that came into operation in 1959 supplying fixed target experiments with 28 GeV beams of protons, and the Intersecting Storage Rings (ISR) proton-proton collider, which began to act in 1971. The next step was represented by the Super Proton Synchrotron (SPS) which was later made into the proton-antiproton collider (at 450 GeV/beam energy) which started to work in 1981. It led to the discovery of the W and Z particles (the carriers of the weak nuclear force) confirming the elegant theory unifying electromagnetic and weak forces (electroweak theory). This discovery by Carlo Rubbia's team, together with the development of a new technique (stochastic cooling) to control the anti-protons and shape them into an intense beam, by Simon var der Meer, earned them the Nobel Prize for Physics in 1984.

Since 1989, these accelerators have also represented the elements of a chain to pre-accelerate and inject electrons and their antiparticles, positrons, into the Large Electron-Positron collider (LEP), where their energy was increased up to 46 GeV, while bunches containing 10^{11} particles were made travel in opposite direction in the same ring, before the head-on collision of two bunches occurred within a detecting unit. By means of this machine physicists could make a detailed study of Z boson, that were

abundantly produced at 92 GeV energy. At 1996, the LEP energy doubled, thanks to superconducting accelerating cavities, reaching 105 GeV per beam.

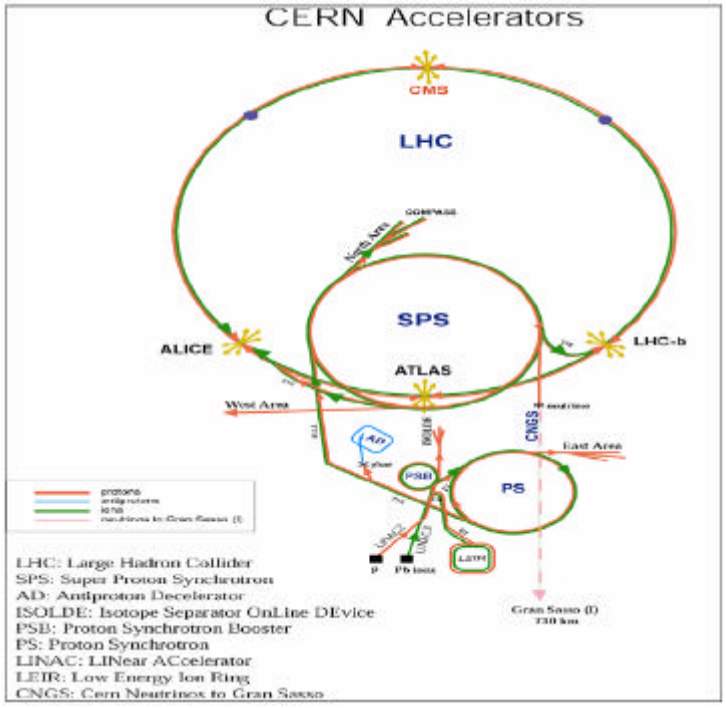


Figure 1.2: The CERN network of interlinked accelerators and colliders.

1.1. HIGH ENERGY PARTICLE PHYSICS CHALLENGES

Particle physicists have found that they can describe the fundamental structure and behaviour of matter within a theoretical framework called the Standard Model. This model incorporates all the known particles and forces through which they interact, with the exception of gravity. It is currently the best description we have of the world of quarks and other particles. However, the Standard Model in its present form cannot give answers to some questions: there are still missing pieces and other challenges for future research to solve.

The masses of the particles vary within a wide range of masses. The photon, carrier of the electromagnetic force, and the gluons that carry the strong force, are completely

massless, while the conveyors of the weak force, the W and Z particles, each weight as much as 80 to 90 protons or as much as reasonably sized nucleus. The most massive fundamental particle found so far is the top quark. It is twice as heavy as Z particles, and weights about the same as a nucleus of gold. The electron, on the other hand, is approximately 350,000 times lighter than the top quark, and the neutrinos may even have no mass at all.

Why there is such a range of masses is one of the remaining puzzles of particle physics. Indeed, how particles get masses at all is not yet properly understood. In the simplest theories, all particles are massless which is clearly wrong, so something has to be introduced to give them their various weights. In the Standard Model, the particles acquire their masses through a mechanism named after the theorist Peter Higgs. According to the theory, all the matter particles and force carriers interact with another particle, known as the Higgs boson. It is the strength of this interaction that gives rise to what we call mass: the stronger the interaction, the greater the mass. If the theory is correct, the Higgs boson must appear below 1 TeV. Experiments at Tevatron and LEP have not found anything below 110 GeV.

Another open question is the unification of the electroweak and strong forces at very high energies. Experimental data from different laboratories around the globe confirm that within the Standard Model this unification is excluded [2]. When scaling the energy dependent constants of the electroweak and strong interactions to very high energies, the coupling constants do not unify. Grand Unified Theories (GUT) explain the Standard Model as a low energy approximation. At energies in the order of 1016 GeV, the electromagnetic, weak and strong forces unify. One of the GUT theories is the supersymmetry (SUSY) that predicts new particles to be found in the TeV range. Many other GUT theories predict new physics at this energy scale.

These and other questions like the elementarity of quarks and leptons, the search of new quark families and gauge bosons or the origin of matter-antimatter asymmetry in the Universe, will be addressed by CERN's next accelerator, the Large Hadron Collider, which is currently under construction.

1.2. LHC

The Large Hadron Collider [3] will collide two counter-rotating proton beams at a centre of mass energy of 14 TeV. This energy is seven times higher than the beam energy of any other proton accelerator to date. In order to achieve an unprecedent luminosity of 1034 *cm*-1*s*-2, it must operate with more than 2800 bunches per beam and a very high intensity. The machine can also be filled by lead ions up to 5.5 TeV/nucleon and therefore allow heavy-ion experiments at energies about thirty times higher than at the Relativistic Heavy Ion Collider (RHIC) at the Brookhaven National Laboratory in New York. Some of the parameters of the new accelerator are listed below:

TOPIC	VALUE	UNITS
Energy	7	TeV
Injection Energy	0.45	TeV
Dipole Field	8.36	Tesla
Number of dipole magnets	1232	
Number of quadrupole magnets	430	
Number of corrector magnets	8000 aprox.	
Luminosity	1034	$cm^{-2}s^{-1}$
Coil aperture in arcs	56	mm
Distance between apertures	194	mm
Particles per bunch	1011	
Number of Bunches	2835	

Table 1.1: Summary of the LHC parameters [4]

The primary task of the LHC is to make an initial exploration of the 1 TeV range. The major LHC detectors, ATLAS (*A Toroidal LHC AparatuS*) and CMS (*Compact Muon Solenoid*) should be able to accomplish this for any Higgs mass in the expected range. To get into the 1 TeV scale the needed beam energy is 7 TeV.

Together with ATLAS and CMS, two other experiments will be fed by the LHC: a dedicated heavy ion detector, ALICE, which will be built to exploit the unique physics potential of nucleus-nucleus interactions at LHC energies, and LHC-B, which will carry out precision measurements of CP-violation and rare decays of B mesons.

The LHC has been prepared since the beginning of the 80's, with a R+D program for superconducting dipole magnets and the first design of the machine parameters and lattice. The CERN Council approved the LHC in 1994. At that time it was proposed to build the machine in two energy stages due to limiting funding. Strong support for LHC from outside the CERN member states was found and CERN Council decided in 1996 to approve the LHC to be built in only one stage with 7 TeV beam energy. Civil engineering works for the LHC are almost completed. The series production of the magnets has already started and works well. The prototypes String I and II have shown the feasibility of high magnetic field cryomagnets connected in series. Installation of the LHC components into the tunnel started after removal of LEP was completed. Injection into first octant is foreseen for 2006. It is planned to complete the machine installation and to start operation in 2007 [5].

1.3. LHC LAYOUT

The LHC has an eight-fold symmetry with eight arc sections and eight long straight sections. Two counter-rotating proton beams will circulate in separate beam pipes

installed in the same magnet (*twin-aperture*). The beams will cross over at the four experiments resulting in an identical path length for each beam.

Each arc consist of 23 identical cells, giving the total length of 2465 m. Cells are formed by six 15 m-dipole magnets and two quadrupole magnets (these dipoles and quadrupoles are called lattice or main magnets). Dipole magnets are used to deflect the beam whereas quadrupole magnets act as lenses to focus the beam. Different from an optical lens, a magnetic lens focuses in one transverse direction and defocuses in the other one. In order to obtain a net focusing effect, two quadrupole magnets are needed (similar to the principle of Galileo's telescope). This is a *FODO*-lattice, in which *F* and *D* stand for the focusing and defocusing quadrupole. In a circular accelerator the *O* stands for dipole used to bend the beam. Small dipole, sextupole, octupole and decapole corrector magnets are installed to keep the particles on stable trajectories. The lattice quadrupole magnets and the corrector magnets of a particular half-cell form a so called short straight section (SSS) and are housed in a common cold mass and cryostat.

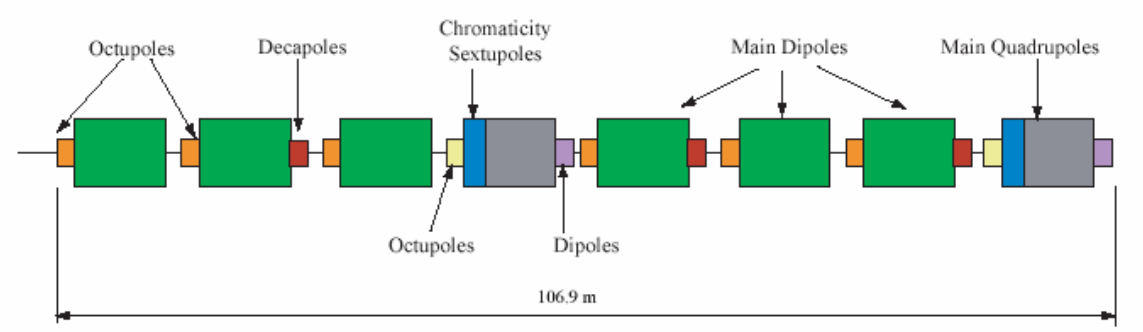


Figure 1.3: LHC cell layout: the six main dipole magnets, two lattice quadrupoles and correctors.

At the beginning and the end of the straight sections a dispersion suppressor cell consisting of four quadrupoles interleaved with four strings of two dipoles each, is in charge of correcting the orbit deviation due to the drift in the energy of the

particles. The four long straight sections where the experiments are located, are formed by the dispersion suppressors and the insertion magnets. These last ones quick the separated beams to a common pipe where they are finally focused by the so called inner triplet magnets in order to get very low beams before collisions inside the detectors.

The other insertions are to be used by systems for the machine operation: beam dump, beam cleaning (collimation), RF-cavities (accelerator units) and injection from preaccelerators.

The injector complex includes many accelerators at CERN: linacs, booster, LEAR as an ion accumulator, PS and the SPS. The beams will be injected into the LHC from the SPS at an energy of 450 GeV and accelerated to 7 TeV in about 30 min, and then collide for many hours.

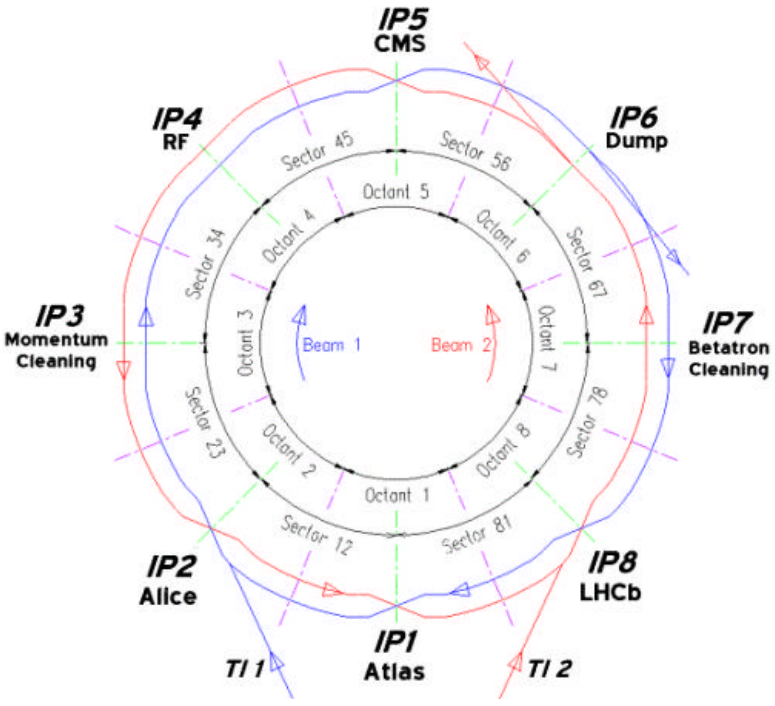


Figure 1.4: Layout of the LHC.

CHAPTER 2.

SUPERCONDUCTIVITY AND SUPERCONDUCTING MAGNETS

2.1. BASICS OF SUPERCONDUCTIVITY

Superconductivity is a remarkable phenomenon whereby certain materials, when cooled to very low temperatures, become perfect conductors of electricity. From experiments [6] it is known today that the resistivity in the superconducting state is at least 10^{12} times smaller than the resistivity in the normal-conducting state.

There exist two reasons for the development of superconducting technologies within accelerator projects: superconducting magnets allow higher particle energies for a given accelerator size, promising a substantial saving in the operating cost of the machine. Normal magnets with iron pole shoes are limited to dipole fields of about 2 Tesla and quadrupole gradients of 10 Tesla/m whereas with superconducting coil fields of more than 8 Tesla and gradients in excess of 200 Tesla/m are safely accessible.

2.2. SUPERCONDUCTING MAGNETS

In a circular accelerator of ions with mass *A* and charge *Q*, the kinetic energy *K* is given by the relation:

$$\frac{K}{A}\left(\frac{K}{A}+2W_0\right)\approx\left(\frac{Q}{A}\right)^2(300BR)^2 \qquad (2.1)$$

where W_0 is the rest energy and *B* the mean magnetic field. The energies are in MeV, the magnetic field in Tesla and the radius in meter. For a high energy proton or electron A = 1, $W0 \ll K$ so $K = W$ and the equation above is reduced then to:

$$W \approx 300BR \qquad (2.2)$$

The LHC is being installed in the 27-kilometres LEP tunnel; hence a 8.3 Tesla dipole field is needed in order to deflect the proton beams. This magnetic field can only be achieved at an acceptable cost using superconducting technology [4] by cooling magnets to 1.9K with superfluid helium. The attainment of 7 TeV in the existing tunnel presents some considerable technological challenges. The small tunnel cross section as well as the need for cost reduction imposes a two in-one magnet design for the main dipoles and quadrupoles. The LHC machine is, actually, two accelerators sharing the same cryostat.

The very flexible LHC optics requires a large number of superconducting magnets, their connections with superconducting bus bars and current leads as part of the electrical circuits. In total, about 10,000 magnets connected within 1,700 electrical circuits will be installed.

2.3. QUENCH

The energy stored in the superconducting magnets is very high (10 GJ in the electrical circuits and 700 MJ in the circulating beams [4]) and can potentially cause severe damages when the superconducting state disappears due to beam losses or cryogenic failures. The resistive transition from the superconducting to the normal-conducting state is called a *quench*. When it occurs, unless precautions are taken, the stored magnetic energy can generate excessive voltages and overheating whose consequences may lead to magnet degradation, a short circuit due to a melted insulation or even an open circuit, which occurs when the conductor burns out.

A reliable active Quench Protection System (QPS) is needed to bring the current down to zero safely when a quench occurs in order to assure the integrity of all the superconducting elements in the machine.

2.4. CRYOGENICS

31,000Tm of material must be spread over 27 km to below 2K in order to ensure a superconducting state of the magnets. The most convenient way to cool helium to this temperature is to reduce the vapour pressure above the liquid bath. When the pressure is reduced in the heat exchanger below 20 mbar the helium, already in a super fluid state, reaches the 1.9K operating temperature.

The bulk of the cold masses remains at atmospheric pressure and is cooled down by the effect of exchange of heat. The machine will be cooled by eight cryoplants, each with an equivalent capacity of 18kW at 4.5 K. Four of these will be the existing LEP refrigerators upgraded in capacity from 12kW to 18kW and adapted for LHC duty. The other four new plants, unlike those of LEP, will be entirely installed on the surface, reducing the need of additional underground infrastructure. The machine cryostats are fed from the cryogenic distribution line (QRL) that runs parallel to the superconducting magnets. The magnets of the arcs and the dispersion suppressors of one octant are housed in a common cryostat of diameter 914 mm, which is about 3 km long with a cold mass of more than 5,000 Tm. The cooldown of the cold mass takes around 14 days.

The first phase of the cool down will be carried out with nitrogen due to its operation simplicity and, above all, its lower cost. It is estimated that about 12 million litres will be evaporated during that phase. Afterwards, 700,000 litres of helium will be necessary to set the whole machine at 1.9 K. The LHC will be the biggest concentration of super fluid liquid in the Universe.

2.5. MAIN MAGNETS AT LHC

There are two main kinds of magnets composing the LHC: dipole magnets, which bend

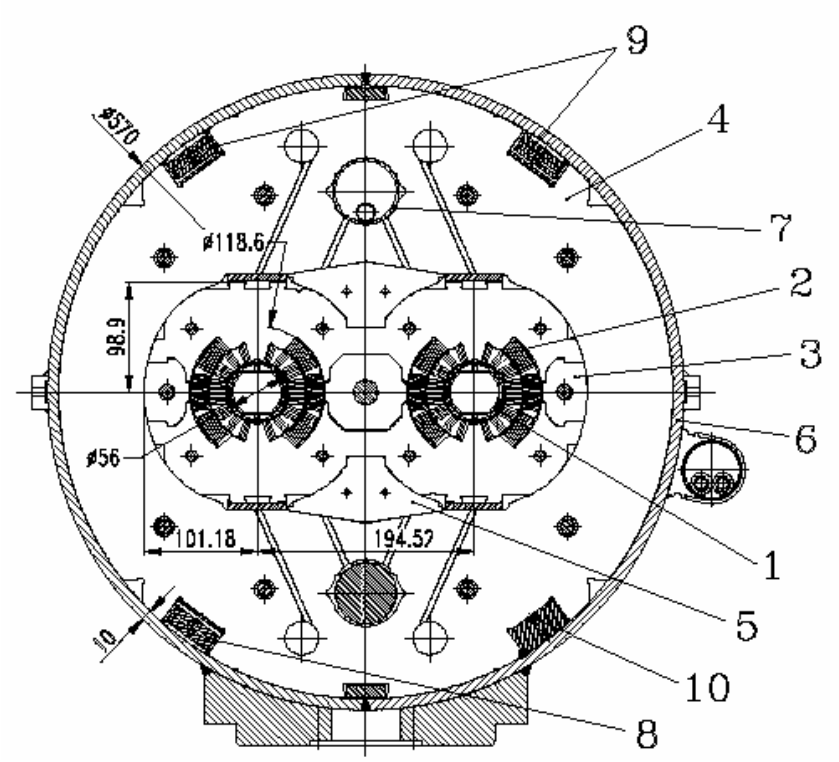
the beam, and quadrupole magnets that focus it. The 154 main dipoles of an arc are powered in series whereas two independent circuits power the quadrupoles of an arc: one for the focusing and one for the defocusing apertures. In the insertions, the apertures of the quadrupoles are either powered individually or in series of two.

2.5.1. Main dipoles

Among the 10,000 superconducting magnets required for the LHC, the most challenging are the 1,232 superconducting dipoles which must operate reliably at the nominal field of 8.3 Tesla, corresponding to the centre of mass energy of 14 TeV, with the possibility of being pushed to an ultimate field of 9 Tesla.

Two technologies for the achievement of fields above 9 Tesla were investigated before the development and construction of dipoles for the LHC: One that uses *Nb*3*Sn* at 4.2 K and another one with *NbTi* technology at reduced temperature. With the first technology a dipole model with a first quench at 11 Tesla was successfully built in Twente University but the coils manufacture's difficulty and the high economic cost makes its use unfeasible. The other more economical alternative, however, suffers from the drawback that the specific heat of the superconducting material and its associated copper matrix falls rapidly as the heat temperature is reduced. This makes the coil much more premature to quenches due to small frictional movements of conductor strands or particle losses.

The cross section of the twin-aperture LHC dipole magnet is shown in the picture below. The coil has a 6-block geometry design which optimizes the field quality and allow more flexibility for small changes during series production.



1-beam tube; 2-SC coils, "6-block" design; 3-austenitic steel collars; 4-iron yoke; 5-iron yoke "insert", 6-shrinking cylinder / He II vessel; 7-heat exchanger tube; 8-dipole bus-bars; 9-arc quadrupole and "spool-pieces" bus-bars; 10-wires for magnet protection and instrumentation.

Figure 2.1: Cross-section of LHC series dipoles [7]

The block geometry design is an approximation of the pure multipole field only achievable if the current distribution around the beam pipe is a function of the angle f given by:

$$I(f) = I_0 \cos(mf) \qquad (2.3)$$

where m is the order of the multipole (m = 1 for dipoles). Current distribution dependence is difficult to fabricate with a superconducting cable of constant cross-section; that is why it must be approximated by current shells or blocks. [8]

The force containment structure consists in coil clamping elements: the steel collars, the iron yoke, the iron insert and the steel shrinking cylinder that contribute to keep the coils in their nominal position. The shrinking cylinder is also the outer shell of the helium tank. This cold mass is 15 m long and 23.8 Tm heavy.

The parameters of the LHC main dipole magnets are summarized in this table:

TOPIC	**VALUE**	**TOPIC**	**VALUE**
Magnetic length	14.3 m	Nominal current	11796 A
Total length	15180 mm	Coil length	14567mm
Operating temperature	1.9 K	Peak field in coil	8.76 T
Stored energy	7.1 MJ	Field at injection	0.53 T
Current at injection	739 A	Field at 7 TeV	8.33 T
J_{NbTi} inner layer 7 TeV	1200 A/mm2	Number of turns inner layer	2 x 15
J_{NbTi} outer layer 7 TeV	1732 A/mm2	Number of turns outer layer	2 x 26
Bending radius	2803.928 m	Bending angle per magnet	5.1 mrad
Number of beams/magnet	2	Number of blocks and layers	6 and 2
Coil inner diameter	56 mm	Inductance per magnet	0.108 H
Coil outer diameter	120.5 mm	Cable length for inner layer	433 m
Mass and cold mass	23.8Tm	Cable length for outer layer	751m

Table 2.1: The main parameters of the LHC dipole magnets [9].

The main dipoles are classified into type A (MBA) and type B (MBB) depending on the electrical connections and the corrector magnets they host. They are alternately located along the arc in order to get a balanced-inductance circuit.

2.5.2. Main quadrupoles

The main quadrupole magnets for the LHC are the twin aperture or lattice quadrupoles (MQ) and the insertion quadrupoles (MQM family, MQY and MQX magnets). The MQ quadrupoles provide the field to focus the particle beam and to keep it near the reference orbit. The LHC will feature 360, 3.25m long lattice quadrupoles, designed

for a 223 Tesla/m gradient field.

The main parameters of these magnets are listed in the following table:

TOPIC	**VALUE**	**TOPIC**	**VALUE**
Magnetic length	3.10 m	Nominal Current	11,870 A
Peak field in coil	6.86 Tesla	Current at injection	763A
Gradient at injection	14.3 Tesla/m	Coil inner diameter	56 mm
Nominal gradient	223 Tesla/m	Coil outer diameter	118.6 mm
Geometrical aperture	56 mm	Coil length	3,184 mm
Inductance per magnet	0.0112H	Number of coil layers	2
Stored energy	0.784 MJ	Number of turns per pole	24
Max. rating current	13 kA	Cable length per pole	160m
Current density 7 TeV (NbTi)	1789 A/mm^2	Total cable length	1280m

Table 2.2: The main parameters of the MQ magnets [9]

Unlike the main dipoles, the two coils sharing the same cryomass on the quadrupoles are powered by independent circuits that shift aperture every magnet in such a way that when the beam is horizontally focused in one aperture it is vertically focused (hence horizontally defocused) in the neighbour aperture. Moreover, the current bypasses every second magnet in order to get a balanced circuit.

The main lattice quadrupoles are housed in the so-called Short Straight Sections (SSS), they also contain several other kinds of magnets (namely octupole, dipole and sextupole correctors, tuning quadrupoles and skew quadrupoles), the protection diodes and the beam position monitors. The other group of main quadrupole magnets is the one used in the insertion for the experiments.

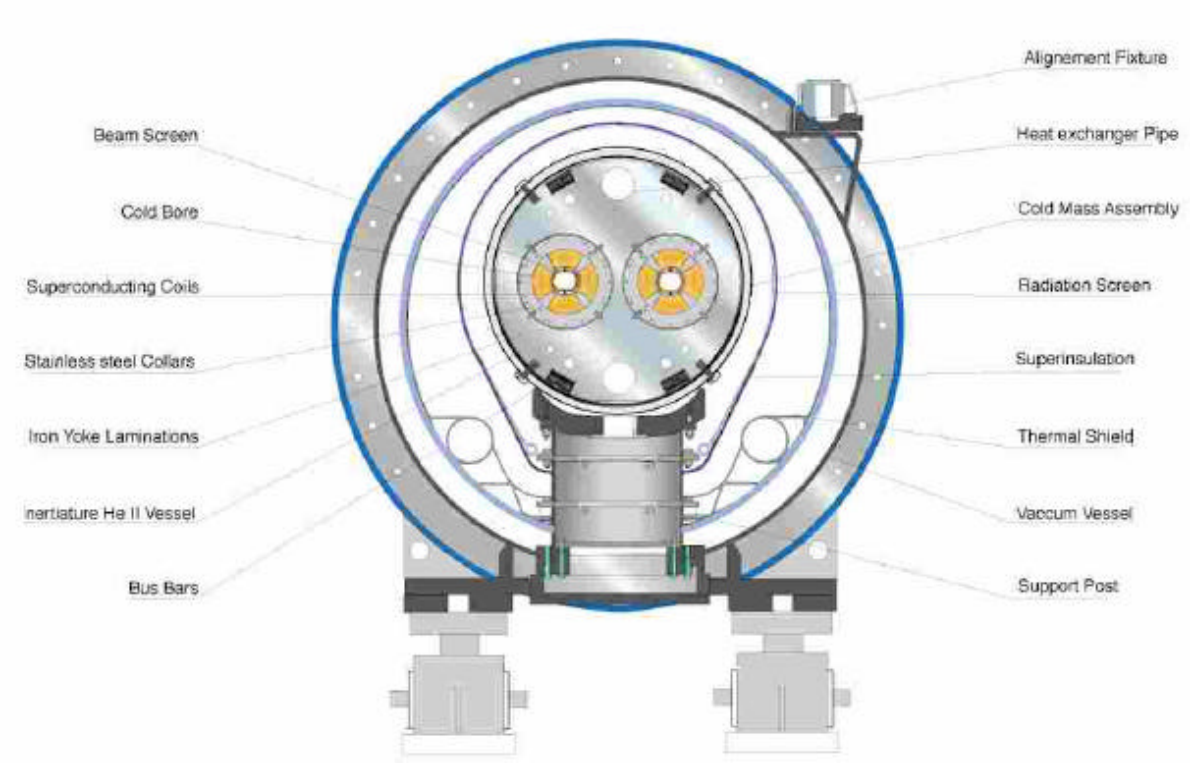


Figure 2.2: Cold mass cross section of the LHC short straight section [10]

2.5.3. Correctors

The corrector magnets of the LHC are smaller than main dipoles or quadrupoles. They are wound with single strand cables and the coils are fully impregnated with epoxy, which reduces the cooling by helium. In order to achieve the field quality, sextupole (MCS), octupole (MCO) and decapole (MCD) magnets (spool piece corrector magnets) are installed at the ends of the main dipole magnets correcting the multipole field errors. Every aperture of each dipole magnet is equipped with a sextupole corrector coil, whereas only every second dipole magnet (type B) will be equipped with octupole and decapole correctors.

The sextupole magnets (MS, MSS) correct the chromaticity and the quadrupole

magnets (MQT, MQS, MQTL) compensate coupling between the transverse planes and adjust the betatron tune (number of oscillations of the beam around the central orbit per turn). Lattice octupole magnets (MO) will be installed to adjust other beam parameters.

About 1,000 small dipole magnets (MCB in the arcs and MCBC, MCBR, MCBX, MCBY in the insertions) will be installed to correct the particle trajectory in both transverse planes, the closed-orbit corrector magnets. All the superconducting corrector magnets of the same type located in the same aperture of an arc are powered in series at a nominal current of 120A for MCO and 550A for the rest. The dipole correctors are powered individually with nominal currents from 60A to 600A depending on their function. [11]

CHAPTER 3.

AB/CO/IS/LS SECTION

CERN is divided into several departments (antique divisions) each one dedicated to different tasks. As well, these departments are divided into groups and then into sections and subsections.

AB department (Accelerator Beam) hosts the groups responsible for beam generation, acceleration, transfer, control and delivery for the CERN accelerator complex. It is responsible for the specification, procurement and commissioning of the equipment for the above systems for the LHC machine, as well as for the power converters for the LHC detectors.

AB/CO group (COntrol) has been created in January 2003. It is responsible for all the controls infrastructure of all the accelerators of CERN. More than 110 people are working in this group to maintain the running installed base but also to study, define, develop and deploy the future control elements that will be used for the future LHC accelerator.

AB/CO/IS section (Industrial Systems), previously called LHC/IAS, has as main functions the definition, selection and implementation of industrial control and supervision systems for the LHC machines equipment, including cryogenics. It also contributes CERN-wide consultancy and support for promoting convergence in industrial control.

AB/CO/IS/LS [12] (Laboratory Systems) sub-section's main activities are concentrated on data acquisition and measurement systems for LHC components or assemblies, either to be used at CERN or the manufacturer's production site.

For these projects it is used LabVIEW or Visual Basic in combination with hardware from National Instruments or other suppliers. Projects are done in collaboration with the requesting users, mainly from AT/MAS and AT/MTM groups.

The data acquisition systems are typically for recording transient phenomena in superconductors requiring from some tens to a thousand channels. The measurement systems typically control devices to vary parameters, such as current, rotation or displacement of probes, with synchronised data acquisition.

It is in this sub-section where I have been working and contributing with the development of the calibration software.

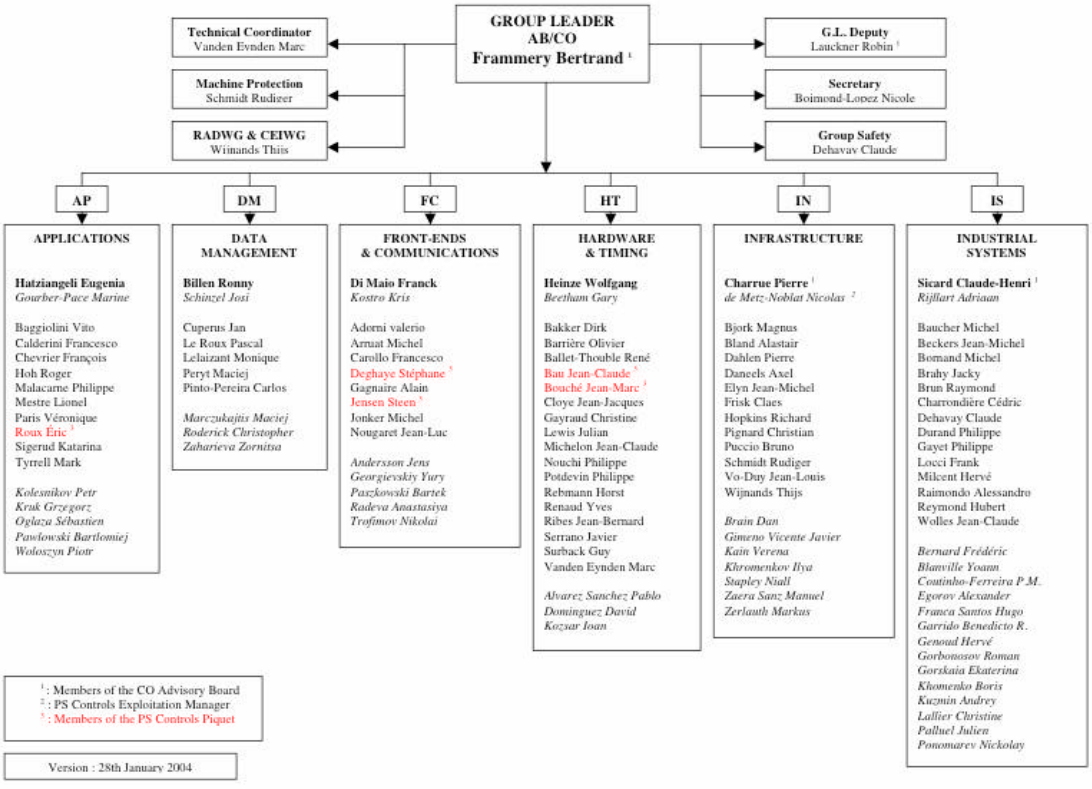


Figure 3.1: AB/CO organigram [13]

CHAPTER 4

MAGNETISM PRINCIPLES

To understand how the data from the magnetic measurements system, used in the magnetic measurement program included in ICCA application, is acquired and treated, it is important to define, firstly, the analysis procedure used to achieve them. Moreover, some definitions and relations about magnetism are shown. [14 .. 20]

4.1. MAGNETIC FIELD AND FLUX DEFINITIONS

In order to understand the way the magnetic measurements system for calibration works, it is important to begin defining some of the important laws and equations related to magnetism.

4.1.1. Magnetic field

Magnetic fields are produced by electric currents, which can be macroscopic currents in wires, or microscopic currents associated with electrons in atomic orbits. The magnetic field B is defined in terms of force on moving charge in the Lorentz force law. The interaction of magnetic field with charge leads to many practical applications. Magnetic field sources are essentially dipolar in nature, having a north and south magnetic pole.

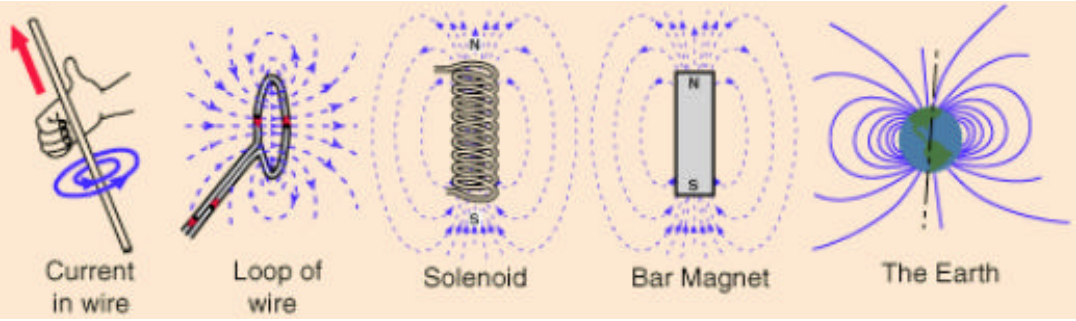


Figure 4.1: Magnetic field sources

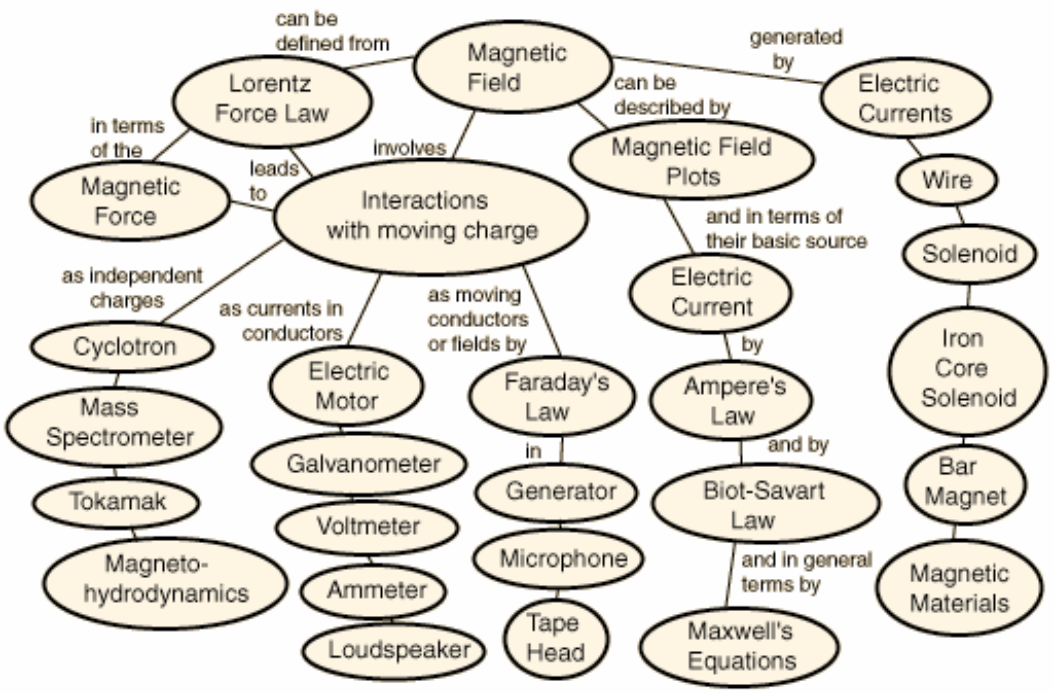


Figure 4.2: Magnetic field's tree

4.1.2. Magnetic Flux

Magnetic flux is the product of the average magnetic field times the perpendicular area that it penetrates. It is a quantity of convenience in the statement of Faraday's Law and in the discussion of objects like transformers and solenoids. In the case of an electric generator where the magnetic field penetrates a rotating coil, the area used in defining the flux is the projection of the coil area onto the plane perpendicular to the magnetic field.

$$\P y = \dot{B} \cdot \P \dot{S}$$
$$[y] = T \cdot m^2 = Wb \qquad (4.1)$$

The contribution to magnetic flux for a given area is equal to the area times the component of magnetic field perpendicular to the area. For a closed surface, the sum

of magnetic flux is always equal to zero (Gauss' law for magnetism). No matter how small the volume, the magnetic sources are always dipole sources (like miniature bar magnets), so that there are as many magnetic field lines coming in (to the south pole) as out (from the north pole).

4.1.3. Maxwell's equations

Maxwell's equations represent one of the most elegant and concise ways to state the fundamentals of electricity and magnetism. From them one can develop most of the working relationships in the field.

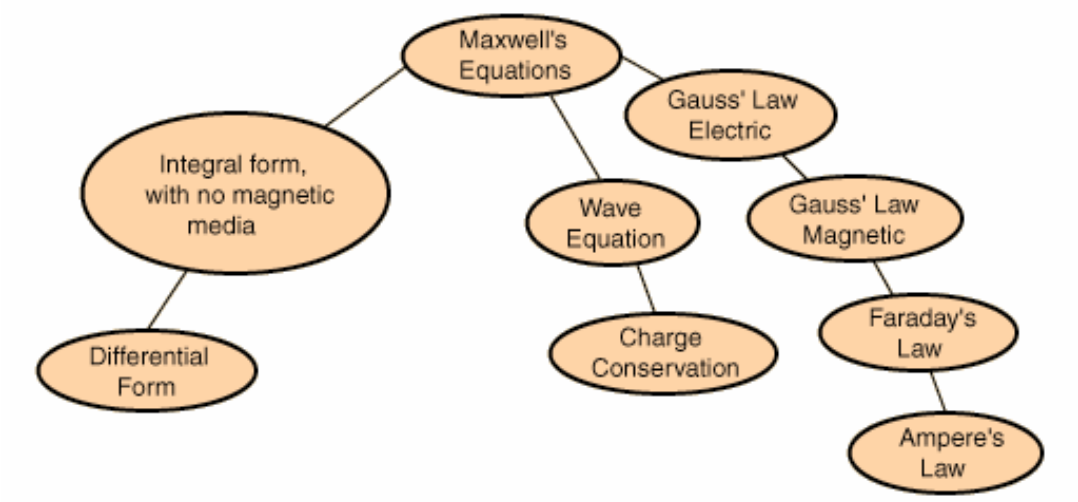


Figure 4.3: Maxwell's equations' tree

4.1.4. Faraday's law

Any change in the magnetic environment of a coil of wire will cause a voltage (emf) to be "induced" in the coil. No matter how the change is produced, the voltage will be generated. The change could be produced by changing the magnetic field strength, moving a magnet toward or away from the coil, moving the coil into or out of the magnetic field, rotating the coil relative to the magnet, etc.

Faraday's law is a fundamental relationship which comes from Maxwell's equations. It serves as a succinct summary of the ways a voltage (or emf) may be generated by a changing magnetic environment. The induced emf in a coil is equal to the negative of the rate of change of magnetic flux times the number of turns in the coil. It involves the interaction of charge with magnetic field.

$$emf = -N_t \frac{\P y}{\P t} \qquad (4.2)$$
$$[emf] = V$$

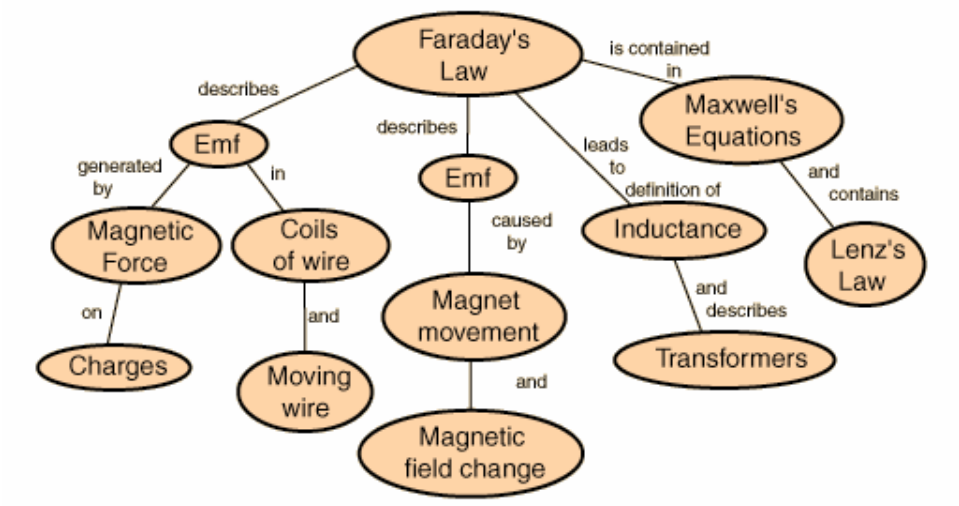


Figure 4.4: Faraday's law tree

4.1.5. Lenz's law

When an emf is generated by a change in magnetic flux according to Faraday's Law, the polarity of the induced emf is such that it produces a current whose magnetic field opposes the change which produces it. The induced magnetic field inside any loop of wire always acts to keep the magnetic flux in the loop constant. In the examples below, if the B field is increasing, the induced field acts in opposition to it. If it is decreasing, the induced field acts in the direction of the applied field to try to keep it constant.

4.1.6. Lorentz's force law

Both the electric field and magnetic field can be defined from the Lorentz force law:

$$\vec{F} = q\vec{E} + q\vec{v}x\vec{B}$$
$$\vec{E} : electric\ \ force$$
$$\vec{B} : magnetic\ \ force \qquad (4.3)$$

The electric force is straightforward, being in the direction of the electric field if the charge q is positive, but the direction of the magnetic part of the force is given by the right hand rule.

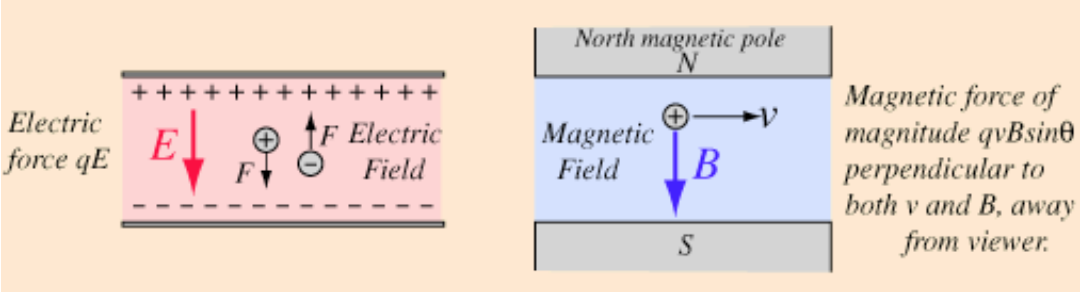


Figure 4.5: Electric and magnetic force

4.1.7. Equations in the system

The magnetic measurements system works in the following way. A constant magnetic field is created while setting current to a magnet (dipole or quadripole). The features of this magnetic field (absolute value, angle, harmonics…) are really important to know since they explain with precision how particles can be deflected, focused by Lorentz'a force… into the accelerators. Probes, a set of coils, are needed for this purpose; as they present an area the magnetic flux can be measured once they are inserted into the magnet. From equation (4.1):

$$y = \int_S \vec{B} \cdot \P\vec{S} = |B||S|\cos(a) \qquad (4.4)$$

The amount of flux depends on the angle that relates the surface vector with the magnetic field vector. This is to say, depends on the orientation of the coils inside the magnet. In order to sweep all the flux increments along the different positions the coils may adopt (a whole turn), they are rotated inside the magnetic field while, due to Faraday's law, the voltage from the coils are read. With this procedure, and with some mathematical relations (multipole expansion of the magnetic field (4.2.1)), any data can be reconstructed. From equation (4.2):

$$y = -\frac{1}{N_t}\int V(t)\P t; \quad \int V(t)\P t = -N_t BS\cos(a); \quad \int \frac{V(a)}{\cos(a)}\P a = -wN_t|B||S|;$$
$$\P t = \frac{\P a}{w}; \quad a \in 0..2p \qquad (4.5)$$

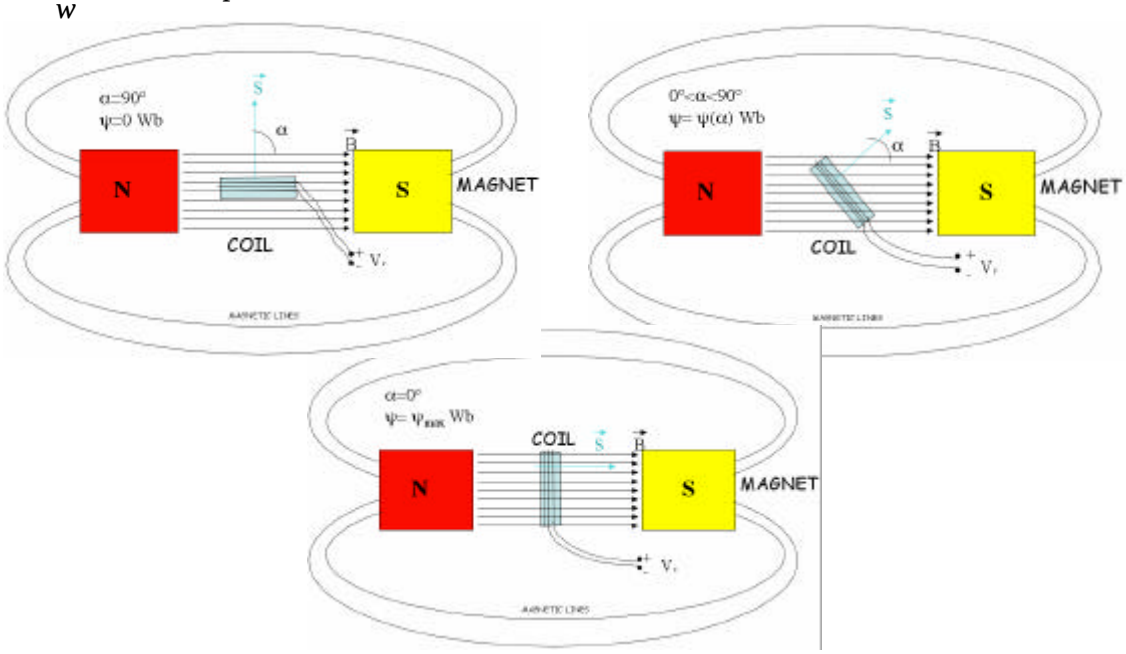


Figure 4.6: Magnetic flux and angle of rotation relation

Voltage delivered by the coil is not the same in these three cases since it depends on the *amount* of magnetic field vectors that goes through the coil area: the magnetic flux. This is to say, it depends on the coil's position with respect to the magnetic field.

4.2. STANDARD ANALYSIS PROCEDURE OF FIELD QUALITY

As explained earlier, magnetic measurements of the LHC magnets are based on a rotating coil system. This method delivers a measurement of the magnetic flux linked with the coil as a function of angular position. Also, the main quantities of interest for field quality characterization are the harmonic coefficients of the expansion of the field. There is a formalism needed to treat the measurements from the rotating coil system in order to obtain these harmonic coefficients.

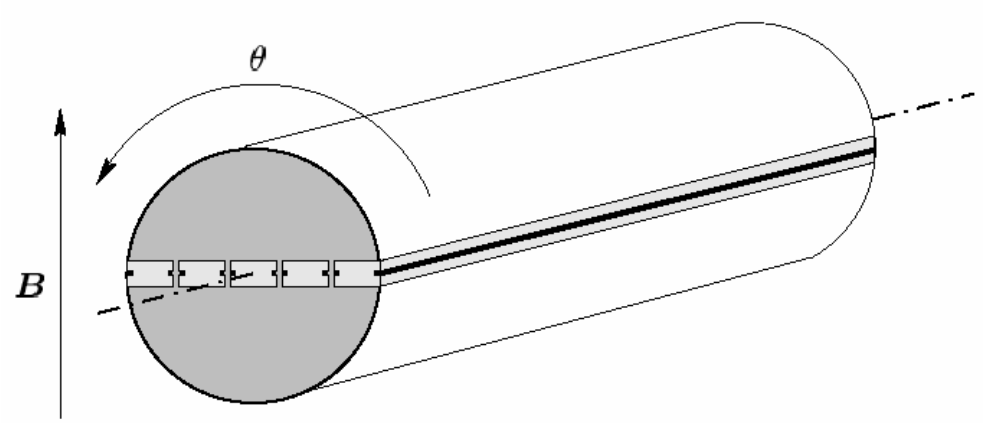


Figure 4.7: Head sector section with five radial rotating coils in a dipole field

4.2.1. Multipole expansion of the magnetic field

As generally accepted for accelerator magnets, and for use in beam optics simulation, the magnetic field *B* is expressed in the 2-D imaginary plane (x,y) using the harmonic expansion in terms of the complex variable z=x+iy :

$$B(z) = B_y + iB_x = \sum_{n=1}^{\infty} C_n \left(\frac{z}{R_{ref}} \right)^{n-1} \qquad (4.6)$$

C_n: non-normalized complex harmonic coef.

R_{ref}: ref. radius (presently 17 mm for LHC).

The harmonic coefficients can be also explicitly written as a sum of their real and

imaginary parts. The normalized coefficients, after a normalizing procedure that depends on the magnet function, are obtained for a normal magnet of order m (m=1 for dipole) using:

$$c_n = 10^4 \frac{C_n}{B_m} = 10^4 \left(\frac{B_n}{B_m} + i \frac{A_n}{B_m} \right) = b_n + i a_n \qquad (4.7)$$

Bm : main magnetic field.

10^4: factor to produce practical units.

C_n expressed in so called *units.*

b_n: normal component of the 2n-pole.

a_n: skew component of the 2n-pole.

4.2.2. Transformation of harmonic coefficients

Two relations among the harmonic coefficients are needed to describe a rigid translation of the reference frame in the 2-D complex plane by a vector ? z=? x+i? y, and a rotation of the reference frame by an angle θ. They are derived from the invariance of the magnetic field:

4.2.2.1. Reference frame translation

If the reference frame is translated by ? z**,** the harmonic coefficients C_k (in the original system x,y) transform into C'n (in the translated system x',y') according to:

$$C'_n = B'_n + iA'_n = \sum_{k=n}^{\infty} \left(\frac{(k-1)!}{(n-1)!(k-n)!} \right) C_k \left(\frac{\Delta z}{R_{ref}} \right)^{k-n} \qquad (4.8)$$

$$n \geq 1$$

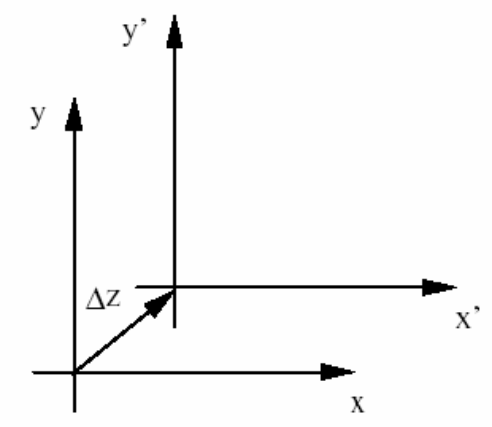


Figure 4.8: Translation of the reference frame

4.2.2.2. Reference frame rotation

If the reference frame is rotated by and angle θ, the harmonic coefficients **C***n* (in the original system *x*,*y*) transform into **C'***n* (in the rotated system *x'*,*y'*) according to:

$$C'_n = B'_n + iA'_n = C_n e^{in} \tag{4.9}$$

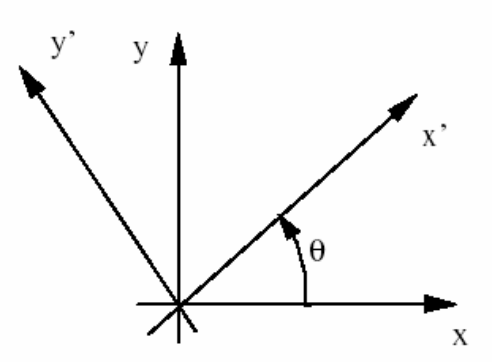


Figure 4.9: Rotation of the reference frame

4.2.3. Principle of measurement with a single turn rotating coil

The measurement by a rotating coil delivers the change of the magnetic flux linked

with the rotating coil surface. This is a model for a single turn, slender coil with two filaments normal to the complex plane (x,y) :

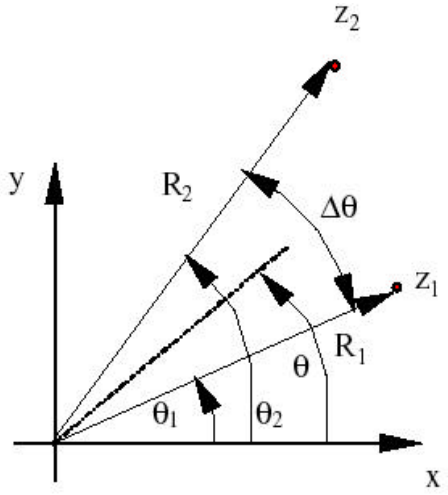


Figure 4.10: Filaments location, normal to the (x,y) plane and with length L, in the complex plane.

The magnetic flux y linked by the couple of filaments of length L (along the ignorable dimension of the magnet) located at $\mathbf{z}_1$ and $\mathbf{z}_2$ in the complex plane can be expressed as:

$$y = LR_e\left[\int_{z_1}^{z_2} B(z)dz\right] = LR_e\left[\sum_{n=1}^{\infty}\frac{1}{nR_{ref}^{n-1}}C_n(z_2^n - z_1^n)\right] \qquad (4.10)$$

Note that this formula can be extended for winding coils. The only difference would be the addition of N_t, the number of winding turns.

The instantaneous position in a rotation is given by:

$$z_1(t) = z_1(0)e^{iq(t)} = R_1 e^{iq_1(t)}e^{iq(t)}$$
$$z_2(t) = z_2(0)e^{iq(t)} = R_2 e^{iq_2(t)}e^{iq(t)} \qquad (4.11)$$

R_1, R_2: Filament radii.

θ_1, θ_2: Initial phases.

With these two expressions, rewritten in term of the average initial phase θ_0, it is obtained:

$$z_2^n - z_1^n = \left(R_2^n e^{inq_2} - R_1^n e^{inq_1}\right)e^{inq} = \left(R_2^n e^{in\frac{\Delta q}{2}} - R_1^n e^{-in\frac{\Delta q}{2}}\right)e^{inq_0}e^{inq} \qquad q_0 = \frac{q_1 + q_2}{2} \qquad \Delta q = q_2 - q_1 \qquad (4.12)$$

With which, the magnetic flux equation can be compacted as follows:

$$y(q) = LR_e\left[\sum_{n=1}^{\infty}\frac{c_n}{nR_{ref}^{n-1}}C_n e^{inq}\right] \qquad \chi_n\text{: coil geometric factors} \qquad (4.13)$$

The complex *coil geometric factors* are related to the coil sensitivity factors of order n by the expression:

$$c_n = \left(R_2^n e^{in\frac{\Delta q}{2}} - R_1^n e^{-in\frac{\Delta q}{2}}\right)e^{inq_0} \qquad (4.14)$$

This form above describes the rigid rotation of an ideal coil around its axis, without variations of the radii and of the opening. This means that the phase q changes periodically throughout the rotation whereas the coil geometric factors χ_n remain constant.

4.2.4. Rectangular coil winding

Up to now, all the equations have been referred to a couple of filaments that is not the real case since rectangular coil winding are used for the measurements. In this case, a correction factor to each side of the coil winding, which will correspond to the relation between the filament approximation and the rectangular approximation, must be applied. This correction is equivalent to the average of the filament approximation over the rectangular 2? x×2? y rotated from the tangent by an angle α. [21]

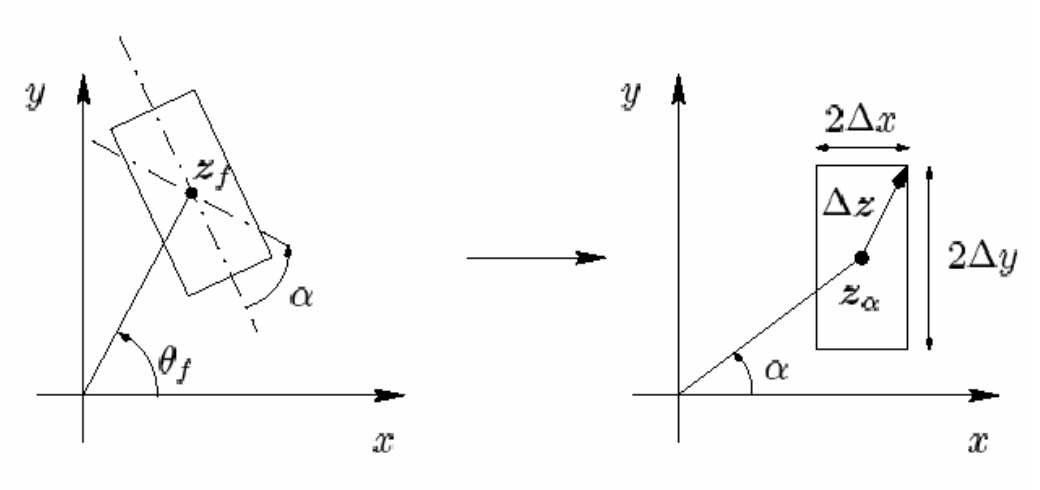


Figure 4.11: Rotation of the coil winding with tilt

The established relations are:

$$
\begin{aligned}
& z_r^n = \Gamma_r(a) z_f^n \\
& \Gamma_r(a) = \frac{(1+x)^{n+2} - (1+x^*)^{n+2} + (1-x)^{n+2} - (1-x^*)^{n+2}}{(n+1)(n+2)(x^2 + x^{*2})} \\
& x = \frac{\Delta z}{z_a}; \qquad \Delta z = \Delta x + i\Delta y; \qquad z_a = z_f e^{-i(a_f - a)} \\
& x^* = \frac{\Delta z^*}{z_a}; \qquad \Delta z^* = \Delta x - i\Delta y;
\end{aligned}
\tag{4.15}
$$

The coil geometric factors for rectangular winding can be calculated using the correction factors with the coil winding at points z_1 and z_2 in that way:

$$
c_n = \Gamma_{r2}(a_2) z_2^n - \Gamma_{r1}(a_1) z_1^n \tag{4.16}
$$

4.2.5. Voltage pickup of a single turn rotating coil

The voltage seen by a single turn rotating coil is, by definition:

$$V = -\frac{\P y}{\P t} = -LR_e\left[\sum_{n=1}^{\infty}\frac{1}{nR_{ref}^{n-1}}c_n e^{inq}\left(\frac{\P C_n}{\P t} + inC_n\frac{\P q}{\P t}\right)\right] \qquad (4.17)$$

As seen, the voltage is induced both by a variation of the field and by a rotation of the coil.

4.2.6. Relation between discretely sampled fluxes and harmonic coefficients

The value of the magnetic flux in each rotating coil measurement is expressed in function of the rotation angle θ_k in a discrete series of points *k* for a total of *N* points. The sampling points are equally spaced over the [0...2p] interval, and the set of sampled points that composes the magnet flux is indicated as y_k. To reconstruct the harmonic coefficients it is used a discrete Fourier transform (DFT) defined as:

$$y_n = \sum_{k=1}^{N} y_k e^{-2pi(n-1)\frac{(k-1)}{N}} \qquad \begin{array}{l} n=1\ldots N \\ y_n : DFT\ complex\ coefficients \\ y_1 : DC\ component \end{array} \qquad (4.18)$$

And then, the inverse DFT signal reconstruction is given by:

$$y_k = \frac{1}{N}\sum_{n=1}^{N} y_n e^{2pi(k-1)\frac{(n-1)}{N}} \qquad k=1\ldots N \qquad (4.19)$$

It is possible to establish a relation between the DFT coefficients and the field harmonic coefficients C_n. This relation, for an even number of points *N* and valid for a single turn idealized coil, is given by:

$$C_n \approx \frac{2}{N}\frac{1}{L}\frac{nR_{ref}^{n-1}}{c_n} y_{n+1} \qquad n=1\ldots\frac{N}{2} \qquad (4.20)$$

4.2.7. Coil sensitivity

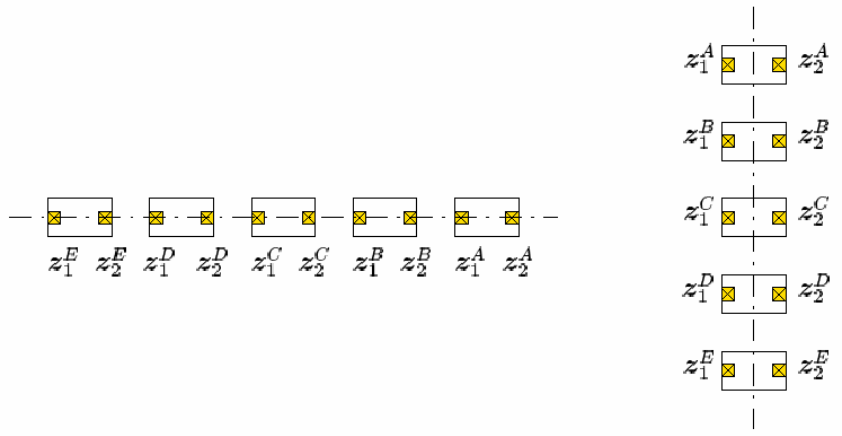
In the case of an ideal coil wound with N_t turns (with negligible winding size), the previous relation can be rewritten in the following form:

$$C_n \approx \frac{2}{N_t}\frac{R_{ref}^{n-1}}{k_n} y_{n+1} \qquad n = 1..\frac{N}{2} \tag{4.21}$$

where the coefficients k_n are the *complex coil sensitivity* coefficients to the harmonic of order *n which* are proportional to the coil geometric factors χ_n introduced earlier:

$$k_n = \frac{N_t L c_n}{n} \tag{4.22}$$

These factors completely describe the geometry of the coils into the mole coordinates and, as said earlier, are independent of the magnetic field. The coil sensitivity is in general a complex number but there are two important, particular cases: that of a radial, where this coil sensitivity is a real number, and of a tangential coil, imaginary number.



$$k_n^{radial} = \frac{N_t L}{n}\left(R_2^n - R_1^n\right) \qquad k_n^{tangential} = \frac{2iN_t L}{n} R^n \sin\left(\frac{n\Delta q}{2}\right) \tag{4.23}$$

Figure 4.12: Radial and tangential coil and complex coil sensitivity factors.

These two cases refer to a single coil reading the magnetic flux, what is called an *absolute* measurement used to determine the main field component. But there is also the so called *compensated* measurement done by connecting different coils with appropriate gains in order to cancel the main field component and, hence, to reach a better radio signal/noise. To obtain the total sensitivity coefficients k_n to an harmonic n from a set of S coils with different sensitivities each one it is used this expression:

$$k_n^{cmp} = \sum_{s=1}^{S} g_s k_n^S \tag{4.24}$$

g_s: gain of the Sth coil.

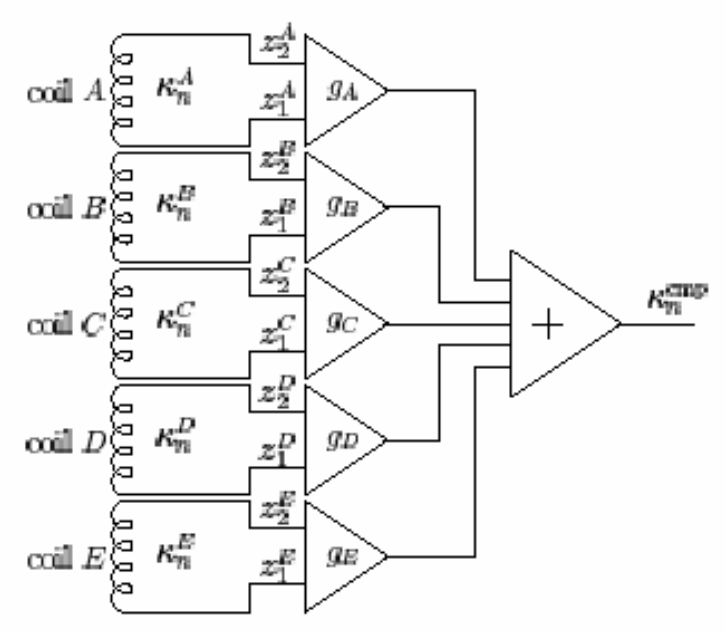


Figure 4.13: Coil sensitivity calculation scheme

Summarizing, for the calculation of the coil sensitivity of the compensated coil set the different sensitivities of each single coil and the gains used for their signals are needed.

4.2.8. Coil data

The known data about the coil, from drawing, that will be useful to calculate the sensitivity factors of a given coil are the following ones:

- The magnetic surface S.
- The inner length L_{in}.
- The inner width W_{in}.
- The thickness T of the groove.
- The number of turns N_t.
- The contraction factor c (usually c=0.9975 for temperature $\leq 70°$ K).
- The radius r_0 from the center of rotation to the magnetic center $z_0 = r_0 e^{iq_0}$.
- The relative parallelism φ_p of the coil with respect to the other coils.

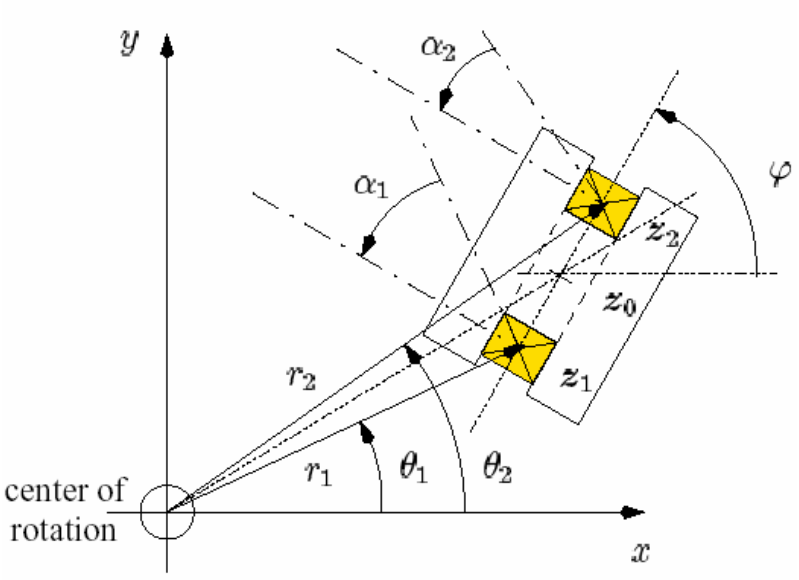


Figure 4.14: Coil positions into the head sector

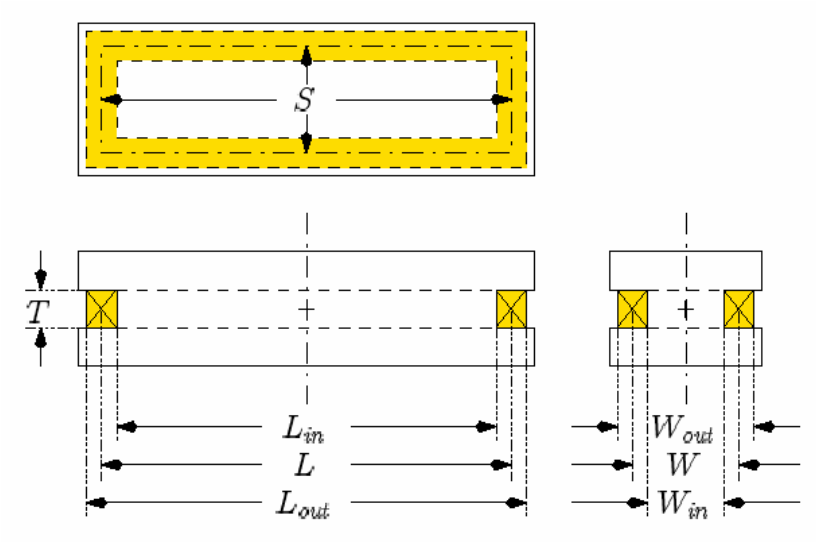


Figure 4.15: Coil dimensions

CHAPTER 5.

STANDARD ANALYSIS OF RAW DATA

In order to generate tables of harmonic coefficients for each measurement, a standard procedure is followed. [14 .. 20]

5.1. NON-NORMALIZED HARMONICS FROM DC MEASUREMENTS

These operations are used for the standard analysis of measurements taken in DC conditions (with constant current in the measured magnet).

5.1.1. Pulse time

Compute the time of the trigger pulse from the angular encoder, for absolute and compensated signals, forward and backward rotations:

$$t_1 = 0\,(s)$$
$$t_{k+1} = t_k + \Delta t_k = t_k + \frac{\Delta t_k}{f}\,(s) \qquad (5.1)$$
$$f = 10^6\ (Hz)$$ f of the reference clock for the integrator counter and for present integrators.
$$k = 1..\,N$$

5.1.2. Conversion

Convert the raw flux increments from integrator ? φ [counts] to ? ψ [Vs], for absolute and compensated signals, forward and backward.

$$\Delta y_k = \frac{\Delta j_k}{K}\ (Vs)$$
$$K = VFC \cdot G_{\text{int}} \cdot G_{amp}\ (counts/Vs) \qquad (5.2)$$
$$k = 1..\,N$$

5.1.3. Coil Voltage and coil voltage offset

The average voltage picked up by the rotating coil during an angular step is calculated directly from the fluxes increments and the time interval as delivered by the integrators:

$$V_k = -\frac{\Delta y_k}{\Delta t_k}\ (V) \qquad k = 1..N \tag{5.3}$$

Compute the voltage offset, invariable during the measurement and caused by the cable connections and amplifier stages, for absolute and compensated signals, forward and backward rotations.

$$V_{off} = -\frac{\sum_{k=1}^{N} \Delta y_k}{t_{N+1}}\ (V) \qquad V_k = V_k - V_{off}\ (V) \tag{5.4}$$

5.1.4. Drift correction

Correct the flux increments for the voltage offset, for absolute and compensated signals, forward and backward rotations.

$$\Delta y_k = \Delta y_k + V_{off}\Delta t_k\ (Vs) \qquad \Delta y_k = \Delta y_k - \frac{\Delta t_k}{t_{N+1}} \sum_{k=1}^{N} \Delta y_k\ (Vs) \qquad k = 1..N \tag{5.5}$$

5.1.5. Signal average

Average the flux increments, for absolute and compensated signals.

$$\Delta y_k = \frac{\Delta y_k^{for} - \Delta y_k^{back}}{2} \ (Vs) \qquad k = 1..N \tag{5.6}$$

5.1.6. Magnetic flux

Integrate the flux increments, which are proportional to the magnetic flux change over an angular step of the encoder, for absolute and compensated signals.

$$\begin{aligned} &y_1 = 0 \ (Vs) \rightarrow q_1 = 0 \ (rad) \\ &y_{N+1} = 0 \ (Vs) \rightarrow q_{2p} = 0 \ (rad) \\ &y_{k+1} = y_k + \Delta y_k \ (Vs) \\ &k = 1..N \end{aligned} \tag{5.7}$$

5.1.7. Fourier transform

Frequency transform the integrated flux (DFT), for absolute and compensated signals.

$$0 \le k \le N-1$$
$$y_n = \sum_{k=1}^{N} y_k e^{-2pi(n-1)\frac{(k-1)}{N}} \ (Vs) \qquad n = 1...N \tag{5.8}$$

5.1.8. Amplitude spectrum

Fold spectrum of the frequency transform, for absolute and compensated signals.

$$N = 2K; \ \mathbf{K} \in Z^+$$
$$\Xi_n = \frac{y_{n+1} + y^*_{N-n+1}}{N} \ (Vs) \qquad n = 1..\left(N/2\right)-1 \tag{5.9}$$

$$N = 2K+1;\ \mathbf{K} \in Z^{+}$$
$$\Xi_n = \frac{y_{n+1} + y^{*}_{N-n+1}}{N}\ (Vs) \qquad (5.10)$$
$$n = 1..\left(N\ {}^{-1}\!/_{2}\right)$$

5.1.9. Harmonics

Compute field harmonics, for absolute and compensated signals.

$$C_n \approx \frac{R_{ref}^{n-1}}{k_n}\Xi_n \qquad (5.11)$$
$$n = 1 \ldots N_m$$

After all these calculations, the results are the non-normalized field harmonics in the reference frame of the rotating coil where the number of harmonic components retained, N_m, is typically 15. All operations on the compensated signal are possible only when the compensated signal is read-out; otherwise, they are skipped.

5.2. FEED-DOWN CORRECTION AND CENTER LOCATION

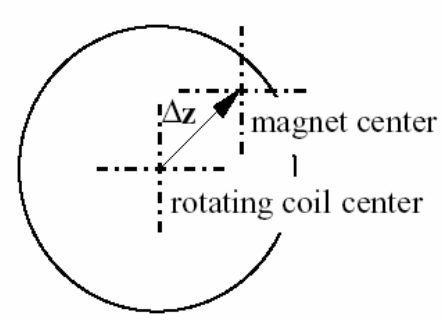


Figure 5.1: Definition of the magnetic centre coordinates

The measuring coil is in general not centred with respect to the magnetic centre of the magnet under measurement. Through the feed-down removal procedure, all the measurements are referred to the magnetic centre instead of the rotating coil centre

as it has been done with the equations up to the moment. The definition of the centre location is different for dipole magnets and higher order multipole. Its procedure is based on cancelling non-allowed harmonics in the measured spectrum.

5.2.1. Centre location

Find the centre location ? **z** (with respect to the coil rotation axis) that cancels the normal and skew 16-pole (order n=8 or/and n=10). These harmonics should be close to zero by symmetry but can be high enough to be little influenced by fabrication errors.

Dipole:

$$\sum_{k=8}^{15}\left(\frac{(k-1)!}{(n-1)!(k-n)!}\right)C_k\left(\frac{\Delta z}{R_{ref}}\right)^{k-n}=0\rightarrow \text{ seven complex roots.} \tag{5.12}$$

$f(\Delta z)=\sum_{k=4}^{7}\frac{\left|C'_{2k}\right|}{\left|C_{2k+1}\right|}\rightarrow$ function to be minimized (by one of the seven roots, the center).

2*m*-pole magnet (*m*>1):

$$\Delta z=-\frac{R_{ref}}{m-1}\frac{C_{m-1}}{C_m}\ (m) \tag{5.13}$$

5.2.2. Feed-down correction

Compute the harmonics (absolute and compensated) in the reference frame translated by ? z.

$$C'_n=B'_n+iA'_n=\sum_{k=n}^{\infty}\left(\frac{(k-1)!}{(n-1)!(k-n)!}\right)C_k\left(\frac{\Delta z}{R_{ref}}\right)^{k-n} \tag{5.14}$$

$n=1\ldots N_m$

The result of these calculations is the *centred* non-normalized harmonics (in a reference frame with origin in the magnet centre), and the centre coordinates with respect to the coil rotation axis.

5.3. NORMALIZED HARMONICS

In order to obtain normalized harmonics in *units*, the non-normalized harmonics must be rotated in the reference frame of the main field first, and normalized to the main field afterwards. The procedure to be followed for a general 2*m*-pole magnet is:

5.3.1. Main field value

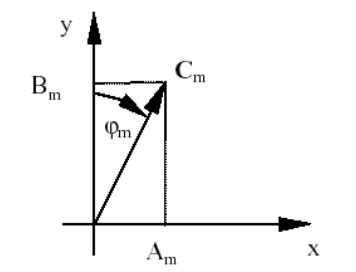
Compute from the absolute harmonics, the main field module. |C*m*|.

$$|C_m| = \sqrt{B_m^2 + A_m^2}\ (T) \tag{5.15}$$

5.3.2. Main field phase

Compute the phase of the main field j_m from the absolute harmonics.

$$e^{ij} = \frac{B_m - iA_m}{|C_m|}$$
$$j_m \in \left[-p/2 \ldots p/2\right] \tag{5.16}$$



5.3.3. Angle

Compute the direction of the main field a_m with respect to the measurement reference frame.

$$a_m = \frac{j_m}{m}\ (rad) \tag{5.17}$$

5.3.4. Rotation

Compute the non-normalized harmonics in the reference frame of the main field, rotating them by a_m.

$$C_n' = B_n' + iA_n' = C_n e^{ina_m}\ (T) \tag{5.18}$$

5.3.5. Normalization

Compute the normalized harmonics of order *n* higher than the main field order *m*.

$$\begin{aligned} c_n &= 10^4 \frac{C_n}{B_m}\ (units) \\ b_n &= 10^4 \frac{B_n}{B_m}\ (units) \\ a_n &= 10^4 \frac{A_n}{B_m}\ (units) \\ n &= m+1 \ldots N_m \end{aligned} \tag{5.19}$$

The results of this procedure are rotated harmonics (absolute and compensated), normalized to the main field for all orders higher than *m*. Note that the harmonic of order *m* has no skew (imaginary) part because of the rotation.

5.4. RECORD OF HARMONICS

The compensated harmonics contain in principle no component below the main field order *m* (as the compensation ideally cancels these components). On the other hand the absolute harmonics have a large component at the main field order *m* and possibly lower orders (due to feed-down) that may pollute the quality of the higher order harmonics. Therefore the standard measurement result should use the absolute

harmonics up to order *m* and the compensated harmonics from there on (if present). Furthermore, through the feed-down correction and the rotation in the main field reference frame some of the harmonics are cancelled by definition. The information on centre location and angle must be therefore added to the final harmonic record.

CHAPTER 6.

ICCA SYSTEM

ICCA means Industry Coil Calibration. It is a system based on magnetic measurements and with the purpose of calibrating coil features inside the moles that are used as probes in the process of testing and checking field properties generated by magnets. ICCA application has been developed in LabVIEW using a standard industrial control system so that it could be fitted in both DIMM and QIMM systems perfectly *[*]*. The program, extensively documented, has been designed to be easy to use at the manufacturers' sites by non-specialist personnel, with the minimum support from CERN. Due to the fact that industry has experience with this kind of systems and the final program for calibrating coils uses some already existing panels and procedures, it requires simple maintenance.

There are available some benches and mini-racks dedicated for calibration purposes exclusively. A power supply, a position control unit and a NMR Teslameter compose it. These three devices will substitute the existing ones in DIMM and QIMM systems while the calibration process. In the software point of view, there are some differences while dealing with one or another system since some of the hardware components (electronic cards for the levelling) and some of the measuring procedures (number of apertures) are not the same.

[*] DIMM means Dipole Industry Magnetic Measurements whereas QIMM, Quadrupole Magnetic Measurements. These are two similar systems composed by hardware (a rack with all the essential components for making magnetic measurements) and software (MMP: Magnetic Measurement Program) used for achieving and reconstructing field features for dipoles and quadrupoles magnets respectively.

6.1. ICCA´s ARCHITECTURE

Since the calibration procedure will be used in both DIMM and QIMM systems and it cannot be understood without any of them, there is not unique hardware architecture with respect to ICCA. This means that the rack destined for calibration, contributing with its own devices, must fit the existing ones. The two different ways of presenting the calibration system are the detailed below.

Generically, the system has a centralized architecture based on a VME industrial standard bus connected via a fast connection card (SUN/PCI-MXI card <-> VME-MXI/VME card/VME crate) to a SUN workstation, that controls and synchronizes every instrument involved in the measurements, running a LabVIEW application. The VME contains ADC cards to measure the electronic gravity sensor output, the value of current during the measurements (although finally the current will be read via GPIB since it will be constant) and the temperature of the mole, digital I/O cards that control the pneumatic brake and integrators to store the voltage values. The LabVIEW application also controls the magnet power supply.

6.1.1. ICCA's architecture in QIMM systems

QIMM systems are used for acceptance tests to quadrupole magnets in industry during their assembly. They have got a simple structure and the hardware that composes this dedicated rack is the following:

- **1 SUN Workstation:** CPU that controls all the system thanks to the LabVIEW software implemented. Sunmms9 in I8 will be used for calibrating moles.
- **2 INTEGRATORS:** Store the absolute and compensated values from the measurement. Into a VME crate.
- **1 ADC:** Reads the current from the power supply in a more accurately way (instead

of using a DVM) and also the angle from the level motor. Into a VME crate.

- **1 DIGIO:** Enables or disables the different brakes. Into a VME crate.
- **1 CPU:** For Real time Acquisistion. Into a VME crate.
- **1 POWER SUPPLY:** Sources current to the system.
- **SIGNAL CONDITIONING:** For the Temperature, Levelling,

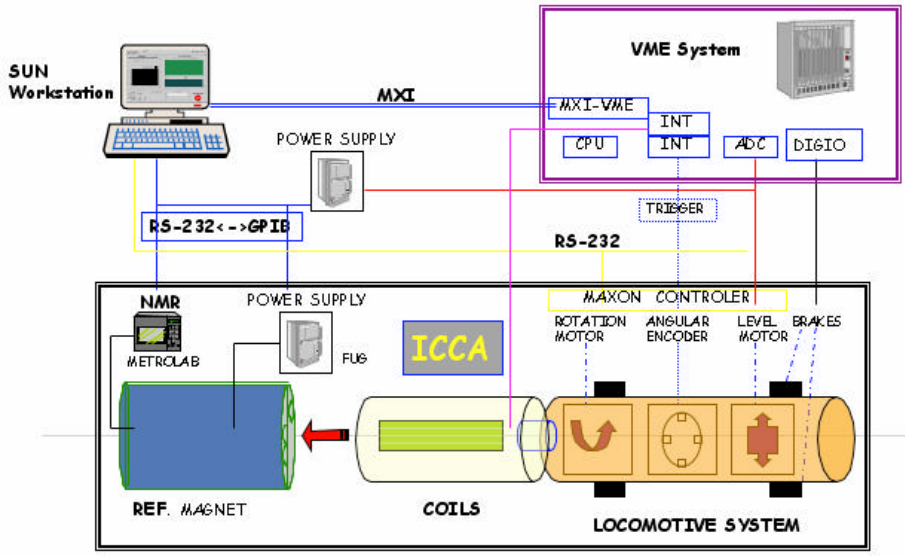


Figure 6.1: ICCA's architecture in QIMM systems

6.1.2. ICCA's architecture in DIMM systems

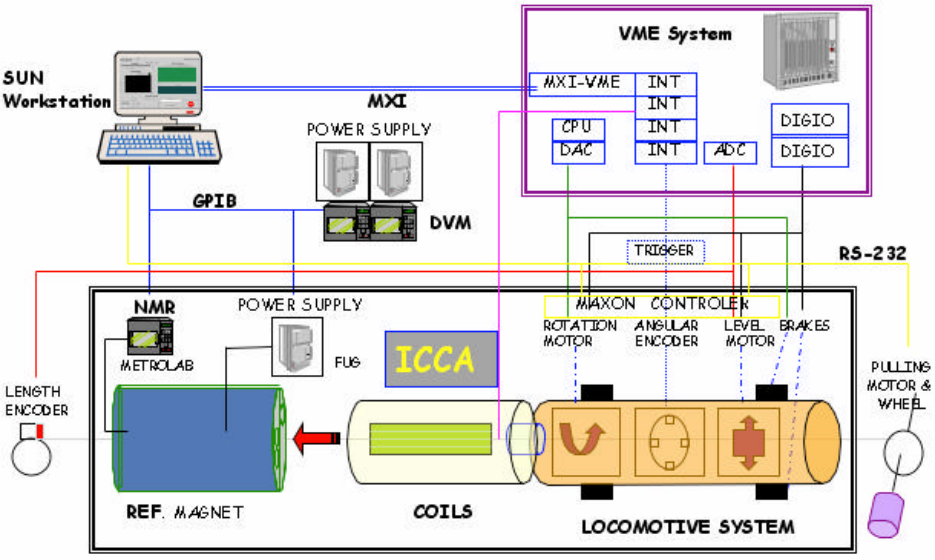


Figure 6.2: ICCA's architecture in DIMM systems

DIMM systems, unlike QIMM systems, are prepared to carry out magnetic measurements with two apertures at a time. Their structure is, then, a little more complicated since not only some extra hardware cards must be connected to the VME bus but also because some new devices are needed for measuring the whole length of dipoles. Nevertheless, only one-aperture measurements are taking place while calibrating the moles.

The list of hardware components of the DIMM rack independently of the ones that may be added with the calibration rack is:

- **1 SUN Workstation:** CPU that controls all the hardware by means of the LabVIEW software implemented.
- **1 DAC:** D/A card that drives the two coil motors rotations.
- **4 INTEGRATORS:** Store the absolute and compensated values generated by the magnetic measurements from the 2 different apertures.
- **1 ADC:** Acquires the level value from the two different apertures. Also, it stores the length of the coil into the magnet.
- **2 DIG-I/O:** These cards are used for the levelling motor for one, the other or both apertures. Identically, for the pressure valves to set the brakes.
- **2 POWER SUPPLIES:** There is one for the main dipole and another one when correctors are measured.
- **2 DVM:** Instead of an extra ADC card as it is used in the QIMM system for reading in an accurately way the current from the power supply, a DVM is used for this purpose. Two in this case as there are two power supplies.
- **1 PULLING MOTOR:** Pulls the mole into the 15 m. long magnets to make measurements along different sections inside the magnet.
- **1 LENGTH ENCODER:** Measures the distance between the mole position into the magnet and a reference final point.

6.2. ICCA's BENCH

The list of devices that can be found in the yellow bench and in the rack linked to ICCA system, including the accessories inside the moles, are explained below. They are installed and ready to be used in the Meyrin site in building 181, in I8.

Figure 6.3: ICCA's rack and bench

6.2.1. Reference magnet

This is the magnet that will create the magnetic field to be measured. Since it is only used for calibration purposes, it is not superconducting and it is not used for bending or focusing particles. It is also important to remark that only one-aperture magnets, as the one shown in the picture below, will be used for the magnetic measurements.

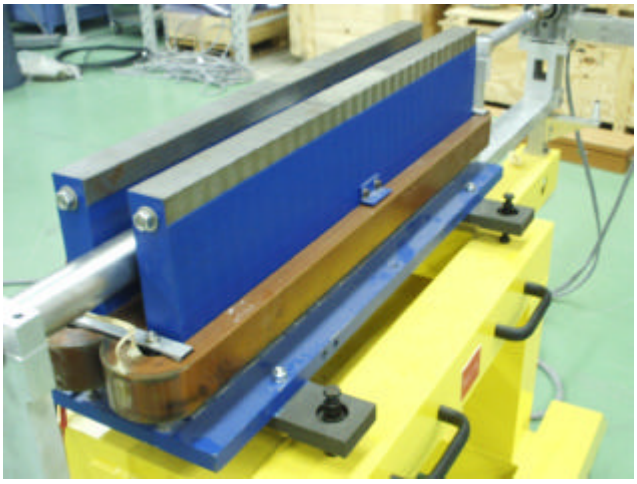


Figure 6.4: Reference magnet at ICCA's bench

6.2.2. Rotation and level motor

A rotating motor can be assembled to the mole. It will be the responsible of rotating the locomotive system: making the coils, inside the mole, turn in both directions. A second motor that will level the set of coils to horizontal with respect to gravity once the mole has been inserted into the magnet, is be also connected to the shaft. These two motors are located outside the mole and the rotation is transferred to the coils by modular shaft spacers. There are two sets of motors as the ones in the picture, one in each of the sides of the shaft so that to allow measurements in the connection side and in the back side.

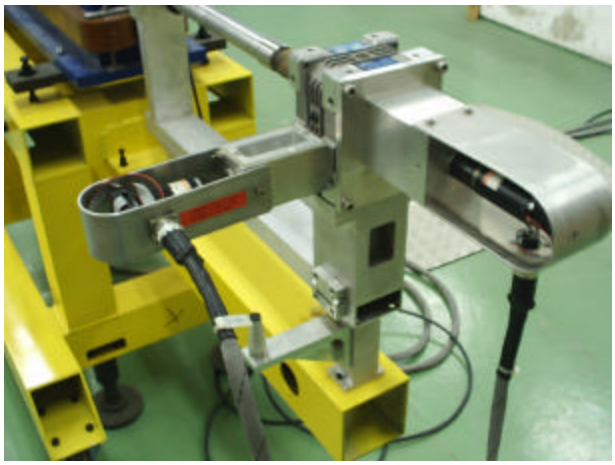


Figure 6.5: Rotation and level motor at ICCA's bench

6.2.3. Inoxidable tube

53/50 mm inoxidable tube identical as the beam tubes in LHC magnets into which the mole is inserted for making the measurements.

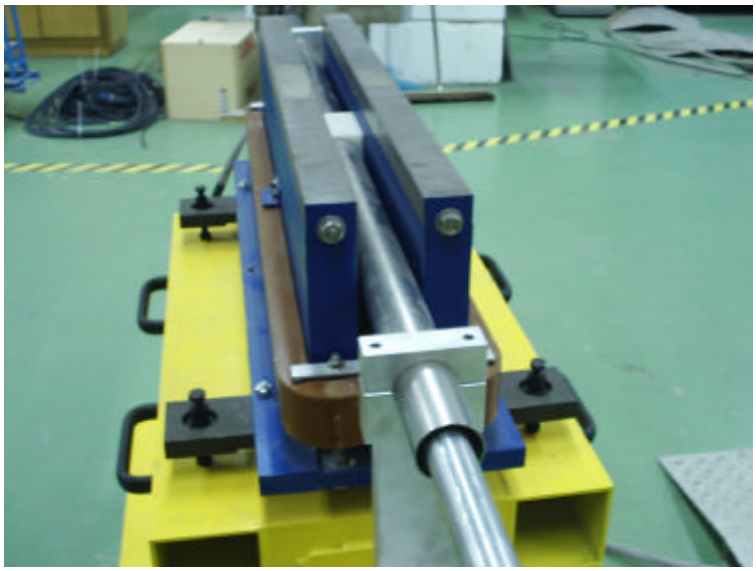


Figure 6.6: Inoxidable tube

6.2.4. Power supply

The power supply gives power to the magnet so that to create the magnetic field. The current to be set during the measurement can be selected previously as positive, negative or both by software. Also, not only constant current can be set to the magnet (remote or manually), but also cycles of current can be edited in order to make AC measurements. For further information, see Appendix 5 FUG POWER SUPPLY NTN 300-60 DATASHEET.

6.2.5. NMR Teslameter

It is a device that measures in a very accurately way the field created into the magnet. The field value, which is read by a probe fixed near the tube, from this

Teslameter should be equal to the one reconstructed with data from the magnetic measurement. For further information, see Appendix 3 NMR TESLAMETERS PT-2025 DATASHEET.

6.2.6. Position Control Unit

With the PCU connected to the mole's encoder, the rotating and levelling motor are totally controlled. For further information, see Appendix 4 PCU 2000 MAXON MOTOR CONTROL DATASHEET.

6.2.7. Mole

A mole is a probe equipped with a 0.75 m long rotating coil and associated angular encoder and motor. It slides into the 50 mm cold bore aperture and contains a light source to transfer the transverse position of the coil rotation axis, and hence the magnetic axis, to external fiducials via a telescope located at the magnet end, however, the location of the beam axis will not be available for this system. Some of the features that can be measured with the moles on the magnet are: integrated field strength, field direction, distance between magnetic axis...

6.2.7.1. Coils

The search coils are made of a 20-wire flat cable wound onto a fibreglass reinforced epoxy core. Each copper wire diameter measures 50 μm and the cable has a width of 1.3 mm. The windings have 400 turns, are 750 mm long and approximately 6.60 mm wide for quadrupole coils and 11.30 mm wide for dipole coils between winding barycentres. A tiny wiring board is inserted inside the coil core to interconnect each individual wire of the multi-wire cable in series [22]. This set of rotating coils (normally 3 or 5) provides voltage signals to be integrated depending on the angle of rotation. With this array of voltage signals, the magnetic flux can be easily calculated.

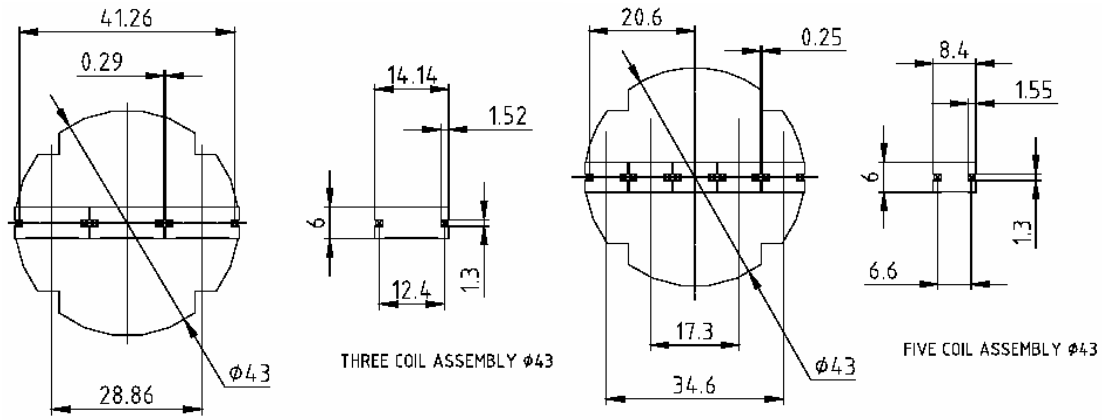


Figure 6.7: Cross section of the harmonic coils in the shaft

6.2.7.2. Incremental encoder

It is fixed on the coils rotation axis and determines their angular position. According to specifications, the accuracy of the main field direction has to be better than 0.1 mrad that is why a 12 bits encoder has been selected.

6.2.7.3. Pneumatic brakes

Pneumatic brakes are set once the mole has been levelled to the corresponding value and allows the coil spins in a secure way (the outer part of the mole does not move).

6.2.7.4. Electronic gravity sensor

The reference axis of the coils is adjusted by rotating the whole mole within ±300 μrad with a precision better than ±50 μrad. This precision is obtained using this sensor.

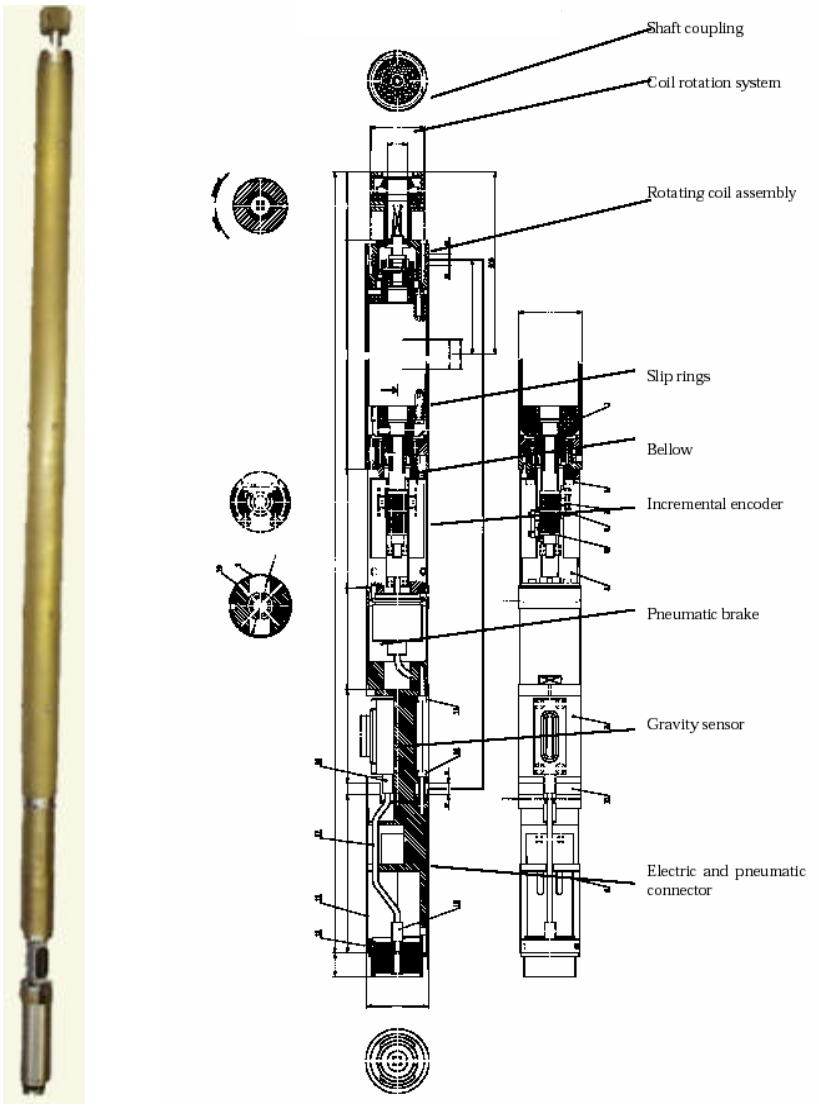


Figure 6.8: Mole and its cross section

CHAPTER 7.

MAGNETIC MEASUREMENT PROCEDURE

7.1. PROCEDURE

The different steps to follow in a magnetic measurement are, in outline, the following ones:

1. The field-measuring mole is inserted into the reference magnet.
2. The rotating motor moves looking for the zero position from which the measured values will start to be acquired. Then, the motor turns exactly $\frac{2}{3p}$ rad in the other sense so that to reach a constant speed while crossing the zero position.
3. The level motor adjusts properly the level of the coils to horizontal (to 0 rad, normally).
4. The brakes are set so that the coil can spin without that the locomotive rotates.
5. The power supply powers the dipole/quadrupole in order to create a magnetic field.
6. The coil spins two turns in one sense and two more in the other. Meanwhile, data from the integrators are acquired thanks to a synchronization system.
7. More than one measurement can be done sequentially.
8. The field is measured by the NMR in every moment.
9. This sequence must be repeated by switching the coil wires manually since two different sets of measurements per coil are needed in some of the cases (the so called connection-side and back-side measurements).
10. Depending on the number of integrators available and the purpose of the measurement, this procedure should be repeated for all the coils inside the mole.
11. For calibration purposes: MOLE PARAMETERS MUST BE UPDATED if it proceeds after analyzing and/or comparing new RAW-DATA generated.

It should be taken into account that there is often a configuration file (in a software point of view) related to each measurement that stores all the necessary parameters to carry out the process successfully (kind of current, number of measurements, integrators' gain...).

7.2. MEASUREMENTS

Each measurement consists in the reading of an *absolute* and a *compensated* signals as delivered by rotating coils over a complete forward and backward rotation. The angular encoder reads the coil angular position. [20]

It exists two different kinds of measurements: the absolute and the compensated one. The absolute signal is obtained from the reading of a single coil (the so called "measuring coil", the one with the highest sensitivity to the main field component), and is used for the determination or verification of the main field component. It is mainly used for testing and checking purposes. The compensated signal (*bucking* signal), that is to say the field harmonics, is obtained as a combination of the signals of different coils, and is used for the determination of the field errors. The *bucking* allows rejecting the main harmonic, so that a higher amplification of the voltage can be applied to the field harmonics detection.

7.3. READING OF COIL VOLTAGE AND INTEGRATION

The two voltage signals (absolute and compensated) from each coil group are sent to VME integrators that amplify the input voltage signal and convert it to a series of variable frequency pulses. These are counted during the time interval determined by two consecutive trigger pulses from the angular encoder. The counts obtained are thus proportional to the integral of the voltage between two encoder trigger pulses. The

result of each integration step, the *flux increments*, is available on the VME bus at each angular interval. In addition, the integrator, via an internal time base, provides the time interval between two subsequent trigger pulses from the encoder.

The flux increments are in units of “counts” from the VFC-counter unit. Counts are proportional to the integrated voltage (Vs), and the constant of proportionality is the product of the gains in the line of amplifiers and of the transfer function of the VFC. For present integrators, different gains can be selected using jumpers. Typical values used are 50 for the *absolute* signal and 500 for the *bucking*.

The time intervals are also in units of “counts” and are obtained from the internal reference of 1 MHz in the counter. Time counts, proportional to the time interval between two encoder pulses, are thus in units of (1/MHz), i.e. in practical terms in units of μs.

The raw-data is considered to be the stored flux increments and the time intervals for the forward and backward rotations, in a total of *N* angular points per rotation (256 in this case) that will be later reconstructed and normalized in order to calculate the field strength and its angle.

CHAPTER 8.

HARDWARE SYNCHRONIZATION

As seen in previous chapters, there are several types of instrument that composes the system. Some of them, like integrators and ADC cards, use a fast VME bus to communicate with the Sun workstation; others, like motors and power supply, use slow RS-232 serial line or GPIB bus. All the instruments must cooperate and be synchronized to achieve good measurements.

Instrument synchronization is very important because affects the measurement precision. The RCM software must synchronize together the angular motor, the integrator and the magnet power supply during a measurement if it is done in AC (current cycles are set). In other versions of the magnetic measurement program, the axial motor must also be synchronous with all the measurement system but the software control for calibration is simplified since the mole stays in the same position during the whole measurements. Also to remark that only DC measurements will be performed for this purpose.

8.1. ENCODER, INTEGRATORS AND ROTATING MOTOR INTERACTION

The 12 bits angular encoder synchronizes the angular motor with the integrators by means of hardware triggers. The encoder is able to send to the integrator two types of trigger:

1. The *sample* trigger: used to communicate to the integrator to read a new voltage value from the coil.

2. The *zero* trigger: used to communicate to the integrator that the coil is in the zero degree position and the data acquisition must begin. The integrator will receive the *zero* trigger each time that the coil execute a complete rotation.

More integrators can be used, but just one must be linked to the angular encoder. The first integrator will propagate the trigger to the next one. The next figure shows how the motor and integrators work together during a measurement:

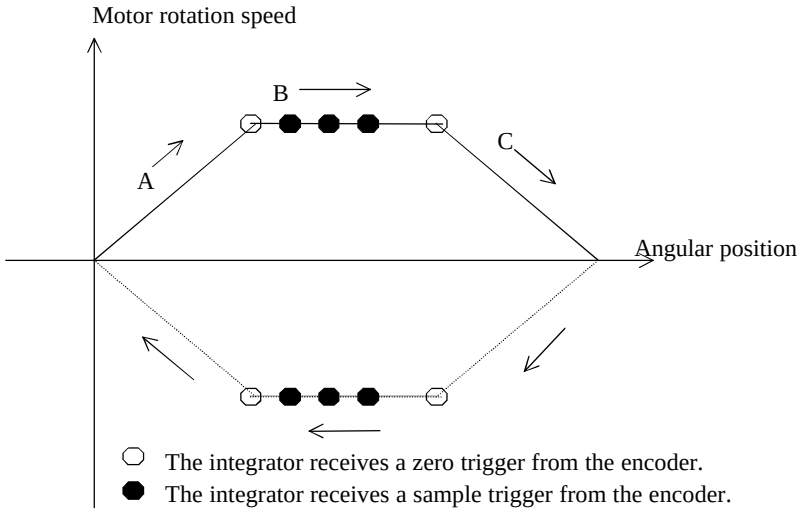


Figure 8.1: Synchronization between the encoder and the rotation motor

A: the angular motor accelerates up to the speed selected by the user. The acceleration is constant and also the speed must be constant during the measurement.
B: the angular encoder sends a zero trigger to the integrator when the angular motor (and so the coil) reaches the start position for the data acquisition. 256 values are acquired for each coil turn. To spread the data evenly the angular encoder sends a sample trigger to the integrator (and the integrator samples a new data) every 1.4 degrees approximately.

$$sample\,rate = \frac{360\text{deg}}{256} = 1.40625 \qquad (7.1)$$

After the coil executes a complete rotation, the integrator receives another zero trigger because the coil is again in the start position and the data acquisition stops.

C: the angular motor is decelerated until it stops. This is the description of the first part of the measurement. In the second part the instruments execute the same task but the angular motor rotates in the opposite way. After the measurement, the motor is in the start position again.

8.2. POWER SUPPLY SYNCHRONIZATION

With the Real Clock Measurement software, the user can define a set of measurements to be executed at different currents. The magnet power supply is an independent device and so it must be synchronized with the rest of the system by the software.

The CPU pools the magnet power constantly. When the current reaches a point where a measurement was defined, the measurement is executed. The SUN cannot pools the magnet power supply in real time because it is usually linked by a low-speed serial line (RS-232, GPIB or serial-GPIB) and so the measurements are executed with a small delay. However, an ADC card could be used in some racks, when the reading of the current is critical.

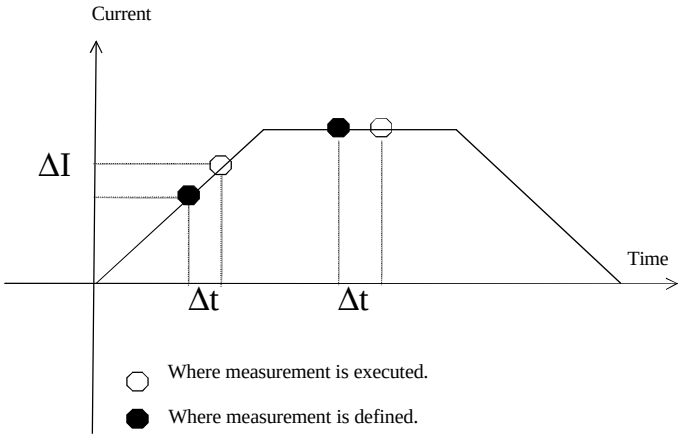


Figure 8.2: Delay while reading current by a low serial line

The delay is never bigger than one second, anyway; hence, this does not affect the measurement executed at constant current. It can be observed that during the measurement with variable current the measurement is executed at a different current with respect to the defined one. The measurements at variable current are usually executed with slow ramp rate and so a delay is not a problem. The measurements will be valid anyway because the current is read directly from the magnet power supply before and after the measurement.

8.3. ROTATING MOTOR SYNCHRONIZATION

The user can select the rotation speed of the rotation motor but the measurements must be executed at constant velocity. The angular encoder sends the zero trigger to the integrators when the start coil position is reached but if the user selects another rotation speed of the motor, then the next measurement will be not correct because the integrator will receive the zero trigger in a wrong position:

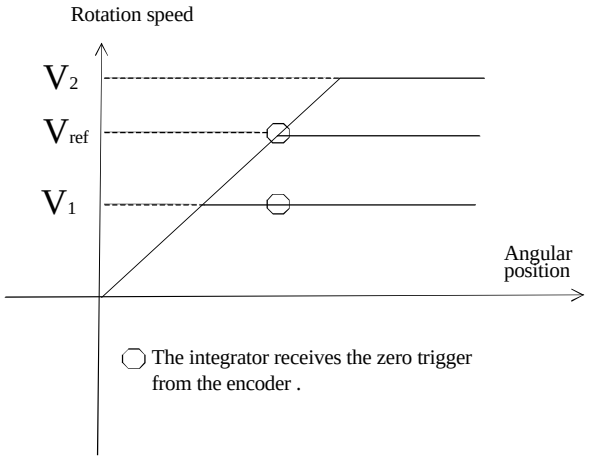


Figure 8.3: Zero trigger position when the rotation speed changes.

If a set of measurements have been executed with rotation speed V_{ref} and the rotation speed is decreased, (for instance to V_1) the integrator will receive the zero

trigger from the angular encoder in late and the data acquisition will start in late (the acceleration is constant).

If a set of measurement have been executed with rotation speed V_{ref} and the rotation speed is increased (to V_2), the integrator will receive the zero trigger from the encoder too early and the measurement will begin at a non constant rotation speed and so the measurement will be non valid.

The RCM software calibrates automatically the angular motor. Each time the user changes the rotation motor speed, the software will search the new start position to execute the next set of measurements with constant rotation speed. The software find the new motor start position by executing a dummy measurement.

To prove that the dummy measurement is enough to find the motor start position let's see what happens when the motor speed is increased and decreased.

8.3.1. Motor speed decrement

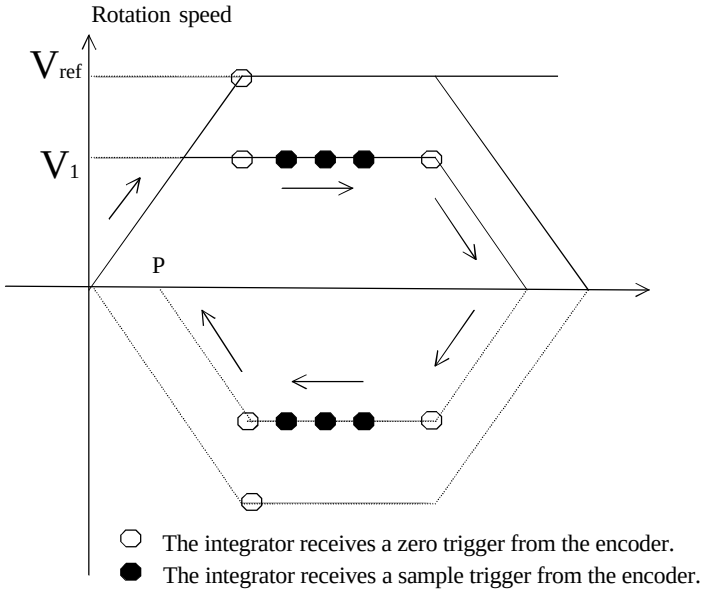


Figure 8.4: Motor speed decrement

During the forward motor rotation, the integrator receives the zero trigger from the encoder in late. The acquisition starts in late too, but all the 256 voltage values are read and the motor is decelerated. During the backward motor rotation, the integrator will receive the start trigger as soon as the motor reach the constant rotation speed because the acceleration and the deceleration speeds are the same. After the measurement the motor will be in a good position (P) for the next measurement. This case is not problematic; the data is valid because values have been read while coils were rotating at a constant speed.

8.3.2. Motor speed increment

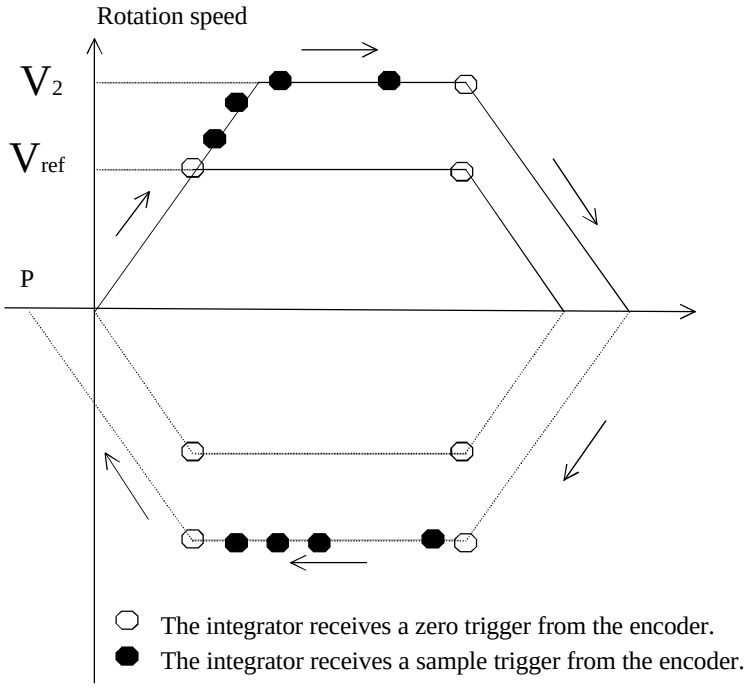


Figure 8.5: Motor speed increment

During the forward motor rotation, the integrator will receive the zero trigger from the angular encoder when the motor is still accelerating. The data acquisition will start too early but after one turn the motor is decelerated until it stops. During the backward motor rotation, the motor will stop in a good position for the next

measurements. Unlike the other case, the data achieved is not valid since the values are not evenly read because of the rotation speed was not constant.

8.4. NMR TESLAMETER

A Teslameter or magnetometer is a useful electronic device used for any application where rapid, fully automatic and very accurate measurements of magnetic fields are of primary importance. It is commonly used in accelerator beam handling since they are easy to use and to control remotely (by serial or GPIB bus) as well as the accuracy of the field value reading is quite good.

8.4.1. Synchronization

Fortunately, it must not be synchronized with any other device of the system since the magnetic field remains always constant inside the magnet. This value, then, must be read at any time to be used afterwards for the analysis.

8.4.2. Theory of operation

Nuclear magnetic resonance is based on a spin-echo nuclear magnetic resonance effect. The spin-echo frequency f_{nmr} and the magnetic field *B* are connected by gyro magnetic ratio g:

$$B = \frac{f_{nmr}}{g}. \qquad (7.2)$$

The physical constant g for different kinds of nuclei is precisely known, so the field strength measurement accuracy is determined by the spin-echo frequency measurement accuracy. Nuclei of the substance in the probe are excited by two short pulses of RF field with the frequency close to the NMR frequency, thus causing the spin-echo signal. Each probe is connected to NMR exciting and receiving electronics by

a multiplexer. A frequency synthesizer is used for both exciting and receiving the spin-echo signal. A measuring cycle is organized by a control module.

There are some limiting factors, which decrease the measurement accuracy. The most significant of them are the signal-to-noise ratio and finite duration of the spin-echo signal defined by field in-homogeneity in the probe volume. Low-noise preamplifiers are placed near every NMR probe to decrease losses of the spin-echo signal in RF cable between the probe and the Magnetometer. The amplified signal is shifted to a low frequency region by multiplying it by two orthogonal signals of precisely known reference frequency close to F_{NMR}. After narrow band low-pass filtering the output signals are digitized by ADC. In computer they are multiplied by Gaussian shaped pulse which width is equal to the spin-echo signal to maximize the signal-to-noise ratio. The carrier frequency is determined according to the spectrum obtained by Fast Fourier Transform. The data measured can be accumulated to give further increase in the relative accuracy of the magnetic fields measurements. [23]

8.5 DATA ACQUISITION

The SUN workstation can read integrators by a VME bus with enough bandwidth to allow real time data acquisition. This data acquisition from the integrators is the most critical part of the system since they do not send any trigger to the SUN workstation directly when the data are ready. The VME CPU card receives the encoder trigger as well as the integrators; that way, it is known when the measurement is finished and the integrator cards are ready to be read by the CPU. Meanwhile, these values are read by the SUN workstation via the VME bus.

The needed acquisition rate depends on the motor rotation speed. The motor speed is not usually bigger than 1 rotation per second and so the maximum rate is:

$$\frac{256\ values}{turn} \cdot \frac{1\ turn}{\text{sec}} = 256\ \frac{values}{\text{sec}} \tag{7.3}$$

That is a value every 3.9 msec approximately, the data acquisition rate required to read a single integrator. In other applications, during multi coil measurements, many integrators must be read at the same time; then, the acquisition rate become proportional to the number of integrators.

CHAPTER 9.

PERIODIC MOLE CALIBRATIONS AND PROCEDURE

9.1. WHAT TO CALIBRATE

The parameters that define a mole are the following ones:

1. Coil surfaces. (m^2)
2. Parallelism between coils. (mrad)
3. Radii of coil rotation. (mm)
4. Distance difference in coils plane. (mm)
5. Perpendicular distance difference to coils plane. (mm)
6. Level zero error. (mrad)
7. Level transfer function. (mrad/V)

The concrete aim of the calibration software developed (ICCA) is to follow an evolution of some of these important parameters of the moles. Most of these are related to the geometry of the coils inside the mole (coil surfaces, radii of coil rotation) and their situation and equivalence with respect to the others (parallelism, distance difference between their planes). That means that with a good calibration and assuring, periodically, that these parameters are well calculated, the geometric coefficients will contribute with real measuring conditions; hence the harmonic coefficients will reflect reliable field features that will be easily differentiable from offsets or noise.

If this is feasible, it will be possible to check, and correct in some occasions, deviations in the mole's structure, from initial features through time, due to its constant handling, variations of temperature, possible mechanical or electrical

damages, manufacturing errors... So that it is like this, a detailed operational specification for the mole's calibration is available in Annex 1.

9.2. COIL SURFACES CALIBRATION

Achieving reliable values of the coil surfaces is very important since they are deeply related to the coil coefficients. As demonstrated earlier, these coefficients are needed in order to reconstruct the exact value of the magnetic flux. In case these are not well calibrated, the final value achieved would not reflex the amount of flux that the magnet really creates. The relation between the coil surfaces, considering perfect radial coils, and the coil sensitivity coefficients can be easily explained by recovering some of the equations presented (4.17) in previous chapters:

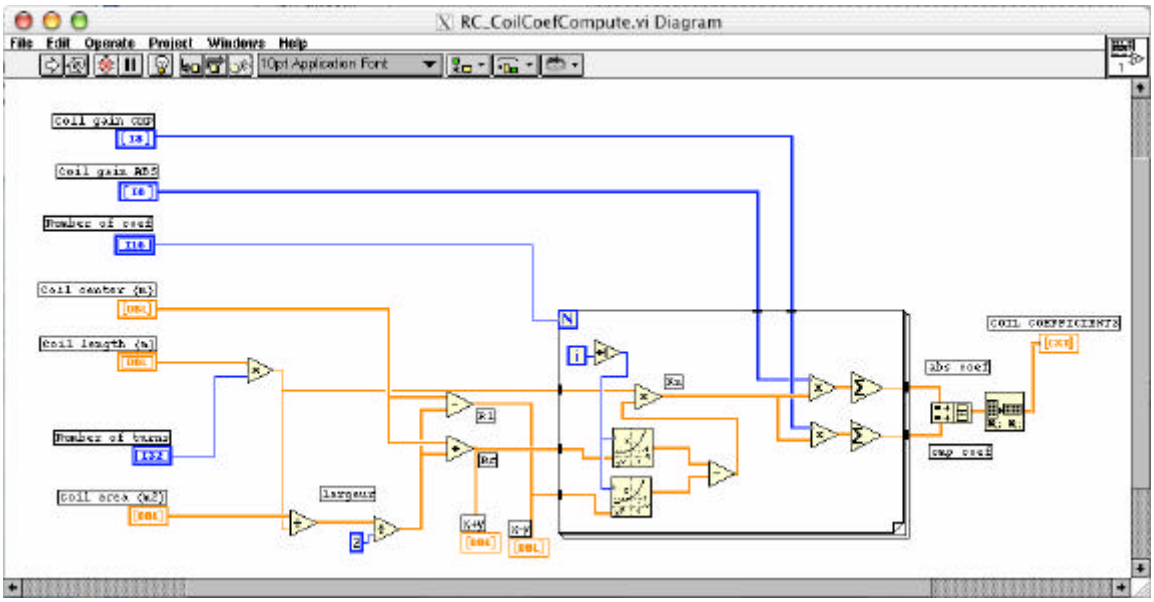


Figure 9.1: Coil coefficients calculation with LabVIEW

$$\mathbf{k_n} = \frac{\mathbf{N_t L}}{\mathbf{n}}\mathbf{c_n} = \frac{\mathbf{N_t L}}{\mathbf{n}}\left(\mathbf{z_2^n} - \mathbf{z_1^n}\right) = \frac{\mathbf{N_t L}}{\mathbf{n}}\left(\left(\mathbf{z_0} + \Delta\mathbf{z_0}\right)^{\mathbf{n}} - \left(\mathbf{z_0} - \Delta\mathbf{z_0}\right)^{\mathbf{n}}\right) = \frac{\mathbf{N_t L}}{\mathbf{n}}\left(\left(\mathbf{z_0} + \frac{\mathbf{S}}{\mathbf{2N_t L}}\right)^{\mathbf{n}} - \left(\mathbf{z_0} - \frac{\mathbf{S}}{\mathbf{2N_t L}}\right)^{\mathbf{n}}\right)$$

$$c_n = \left(z_2^n - z_1^n\right)$$

$$z_2^n = \left(z_0 + \Delta z_0\right)^n; z_1^n = \left(z_0 - \Delta z_0\right)^n \qquad (9.1)$$

$$\Delta z_0 = \frac{S}{2N_t L}$$

To calculate the surface value of one coil inside the mole, after connecting the absolute integrator to it, a standard magnetic measurement (see next section for further details) must be performed. As the field value from the Teslameter will be extracted and the magnetic flux can be reconstructed from the measurement raw-data obtained, the calculation of the new data can be easily calculated as:

$$\left|S_{c_{REAL}}\right| = \frac{f_{\max}}{|B|\cos(a)} = \frac{f_{\max}}{|B|} \qquad (9.2)$$

The REAL coil surface value is given when the angle between the surface vector and the magnetic field vector is zero. (see figure 4.6). This value will be compared to the some time ago calculated one. If the difference between both exceeds the acceptable limits, 300 μm^2, the old value can be overwritten by the new one, in all the corresponding files, after saving it in a historic file. In case that more than one measurement is performed sequentially, the average of the resulting surfaces will be saved.

9.3. PARALLELISM BETWEEN COILS

The aim of this calibration is to check that all the coils inside the mole are coplanar, that is to say, if there are not big differences between the angle created by the magnetic field vector and the axis of the coils. Unlike the coil surfaces, this parameter cannot be corrected but only checked. The procedure followed in the

program is the next one: It must be performed as many sets of measurements as number of coils inside the mole in order to calculate a field angle value from each coil since there is only one integrator for absolute measurements per coil (the ideal would be to profit each set of measurements for the calculation of all the angles of the coils). For all these measurements, the levelling value of the coils is expected to be the same (always to 0 mrad, for instance, as it is done in the program) so that to compare the reconstruction of all the field angles to a same reference tilt sensor value. These are stored while they are obtained and later they can be compared. If the greatest angle difference between two of the coils exceeds the maximum tolerance allowed (selected by the user) may this mole has got a mechanical default, coils are not in the same plane, and hence it is not an appropriate tool to use as a probe. The program developed will warn about this since it cannot modify physically the orientation of the coils.

In this case, the accuracy and reproducibility of the levelling system and its software is very important since a deviation in the adjustment of the reference axis bigger than 50 μrad may imply the acceptance of bad results due to the difference between angle references for each coil.

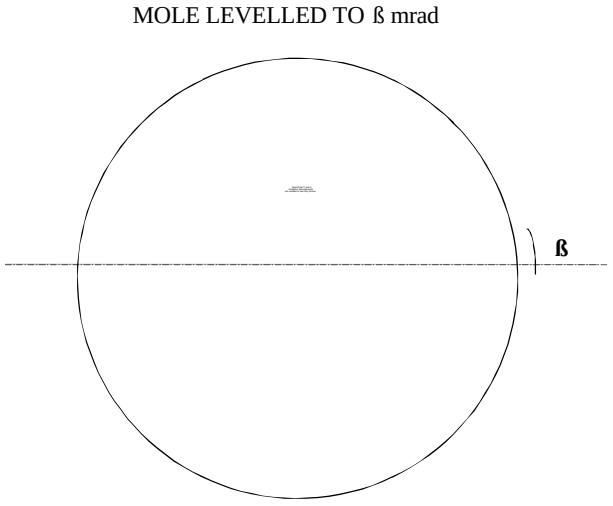


Figure 9.2: Are all the calculated field angles equal to the reference β mrad?

9.4. LEVEL TRANSFER FUNCTION

The level transfer function is a parameter that allows knowing whether the tilt sensor attached inside the mole works in a proper way and whether it is linear in the working region or not (between ±2 mrad). This parameter is a relation between the reconstructed field value (in mrad) achieved from the measurements of each coil and the reading of the levelling sensor (in V). If the results demonstrate a good correlation between those variables, the result should be a straight line passing through three coordinates (or even more in the mentioned range, although the software is only presented for three different ones) with a slope value approximately equal to 1.454.

$$\mathrm{LTF} = \frac{\text{angle from the measurement(mrad)}}{\text{gravity sensor value(V)}} \qquad (9.3)$$

$$\frac{0.5\,\mathrm{deg}}{6V} \cdot \frac{prad}{180\,\mathrm{deg}} \cdot \frac{1000\,mrad}{1\,rad} = 1.4544\ mrad/V$$

The procedure to reach the final level transfer function is simple since it has few variations with respect to the acquisition of previous parameters for calibration but with the difference that the number of measurements increase. Up to a total of 6 different sets of valid measurements (each set can be composed of n measurements) per coil must be accomplished: there are three different levelling values (0 mrad, +2 mrad, -2 mrad) and two measurements to be carried out per each one (one from a connection side and another one from the back side). After calculating the average of all of them, the desired value is achieved. If there would be a considerable difference from the expected value, that would probably mean that there is a problem with the gravity sensor or that the physical position of the coil is not correct.

9.5. LEVEL ZERO ERROR

Profiting the previous procedure, the level zero error can be corrected, too. The field directions in connection and in back side should be equal independently of the levelling value (tilt sensor reading). If they are different, the level zero error is corrected with the average of them. There are two interesting angles to take into account, the field angle and the mole angle:

$$q_{field} = \frac{q_{conn} - q_{back}}{2}$$
$$q_{mole} = \frac{q_{conn} + q_{back}}{2} \qquad (9.4)$$

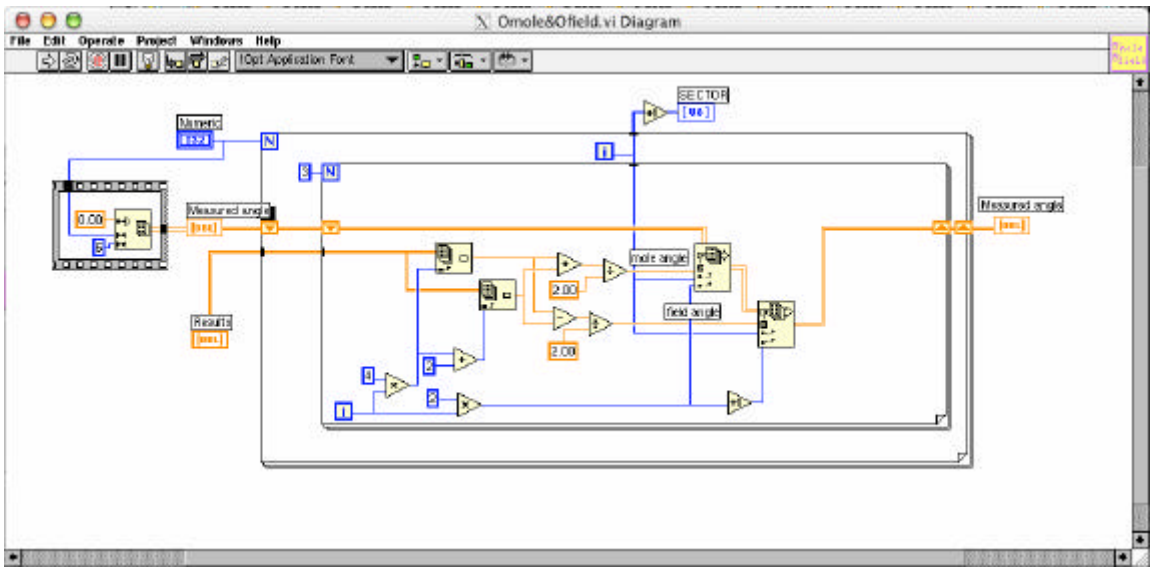


Figure 9.3: Field and mole angle's calculation in LabVIEW

The field angle must be next to zero since the connection-side and the back side angles from the measurement are expected to be equal (as long as the calibration bench is stable and it does not move) whereas the mole angle must be nearly equal to the one read from the gravity sensor.

CHAPTER 10.

ICCA SOFTWARE

ICCA has been totally developed in LabVIEW 5.1. There are several reasons for having used LabVIEW but the most important one is that a program destined for magnetic measurements (MMP) had already been designed in this language. Many versions of MMP have been developed by the AB/CO/IS/LS subsection since requests for different systems and with different analysis and procedure applications increase. One of the versions used at QIMM systems has been recovered, modified and adapted in order to apply the calibration requirements.

ICCA is formed by more than 400 subVI and more than 20 different panels can appear while dealing with the program. Since LabVIEW's code cannot be printed as easily as it could be done with another high level programming language (C, Java…), only a few programming examples, structures and techniques will be shown (but no utility matters; for this topic, see the user's manual in Annex 2.). Moreover, there are two attached text files where all the changes done to ICCA project (ICCAchange.txt) were updated regularly and the different releases generated by those updates: addition of new important VI, changes in structures, code compacting into VI, addition of controls or indicators… It has been a useful tool to refresh and recover changes done some time ago from previous versions.

10.1. LABVIEW

LabVIEW programs are called virtual instruments (VI) and they are composed of three main parts: a front panel, a block diagram and a icon-connector.

The front panel allows the user to set the input values of the program and to view the outputs from the VI block diagram. Because the front panel is analogous to a front panel of a real instrument, the inputs are called controls and the outputs are called indicators. There are a variety of controls and indicators hence the programmer can create the front panel easily identifiable and understandable.

Each front panel has an accompanying block, which is the VI program. The language used to build this diagram is graphical and it is called language G. The block diagram replaces the normal source code of other languages and its components represent program nodes; for example: for loops, case structures, arithmetic functions… The components are *wired* together to define the flow of data within the block diagram.

The part of the icon-connector is used to turn a VI into an object (subVI) that can be used as a subroutine in the block diagrams of other VI. The icon graphically represents the VI in the block diagram of other VI. The connector terminals determine where the inputs and outputs must be wired on the icon. The terminals are analogous to subroutine parameters. They correspond to the controls and indicators on the VI front panel.

LabVIEW sets a special hierarchy at the VI components. After creating a VI it can be used as a subVI in the block diagram of a higher-level VI. There is no limit on the number of layers in the hierarchy.

10.2. PROGRAMMING STRUCTURES

10.2.1. Index VI's structure

The main menu's diagram is composed by a 14 cases structure, located into a main loop, through which the flow of the program can be passed to the NMR device control, to

the power supply control, to the panel for the creation of configuration files, to the execution of measurements, to different panels to recover data…

The circled code is a common structure used when there are a lot of controls among which the user can choose. Depending on the boolean output index set to true in the array (button pressed or action taken by the user), a concrete code will be executed from the case structure. In the case shown below, when no buttons are selected, and depending on other choices from the front panel, some indicators are refreshed or updated by information extracted from some files.

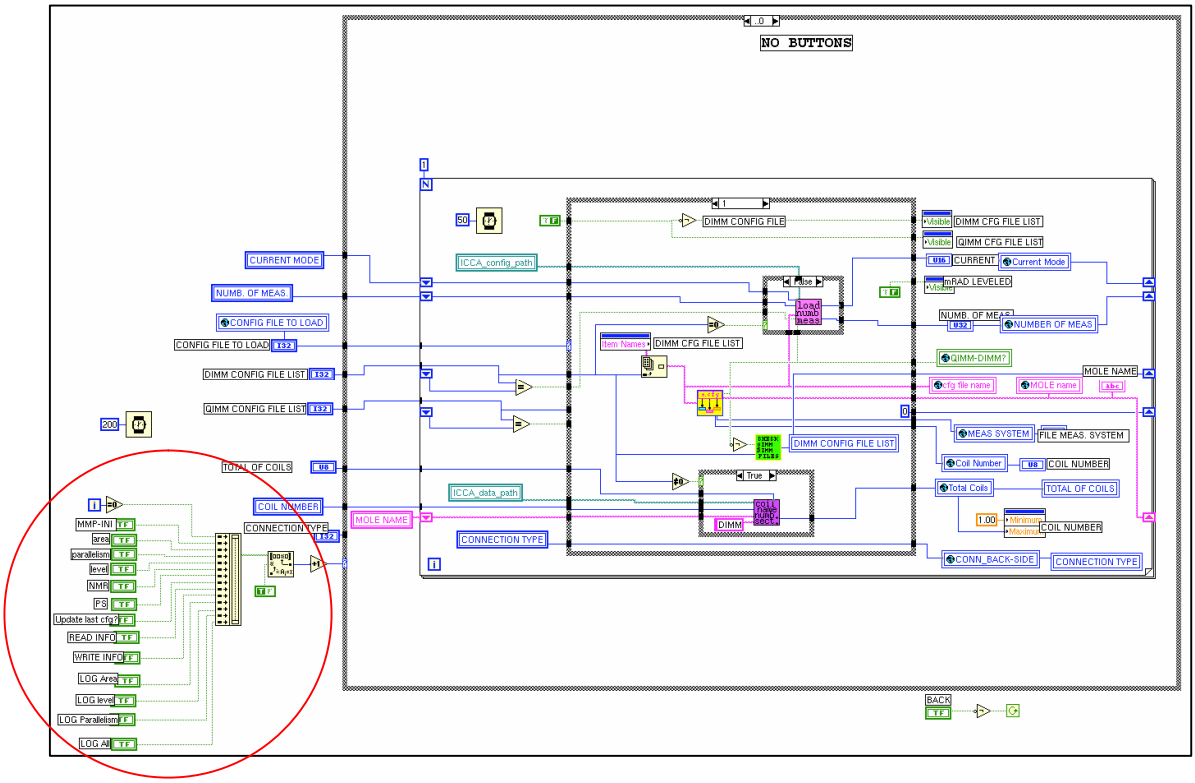


Figure 10.1: Frame "0" in Index VI's diagram block

10.2.2. Area VI's structure

This is a part of the code inside the initialization frame of the Area VI's diagram. This code, inside a for loop, is reached either when a set of measurements has immediately

finished or because data from last measurements (from the last *.CFG file) want to be analyzed for recalculating the coil area. In any case, information from measurements are recovered from *.RF files (code inside a black circle).

After recovering and detaching data of every measurement, through some analyzing stages (frame 0), and after achieving a field locked value from the Teslameter (frame 1, inside a green circle) the new surface value, the harmonic coefficient C_n, the field angle, the temperature of the measurement, the maximum value of the absolute flux and the NMR value of each measurement referred to the coil selected will be displayed (frame 1 and frame 2) and ready to be saved if proceeds.

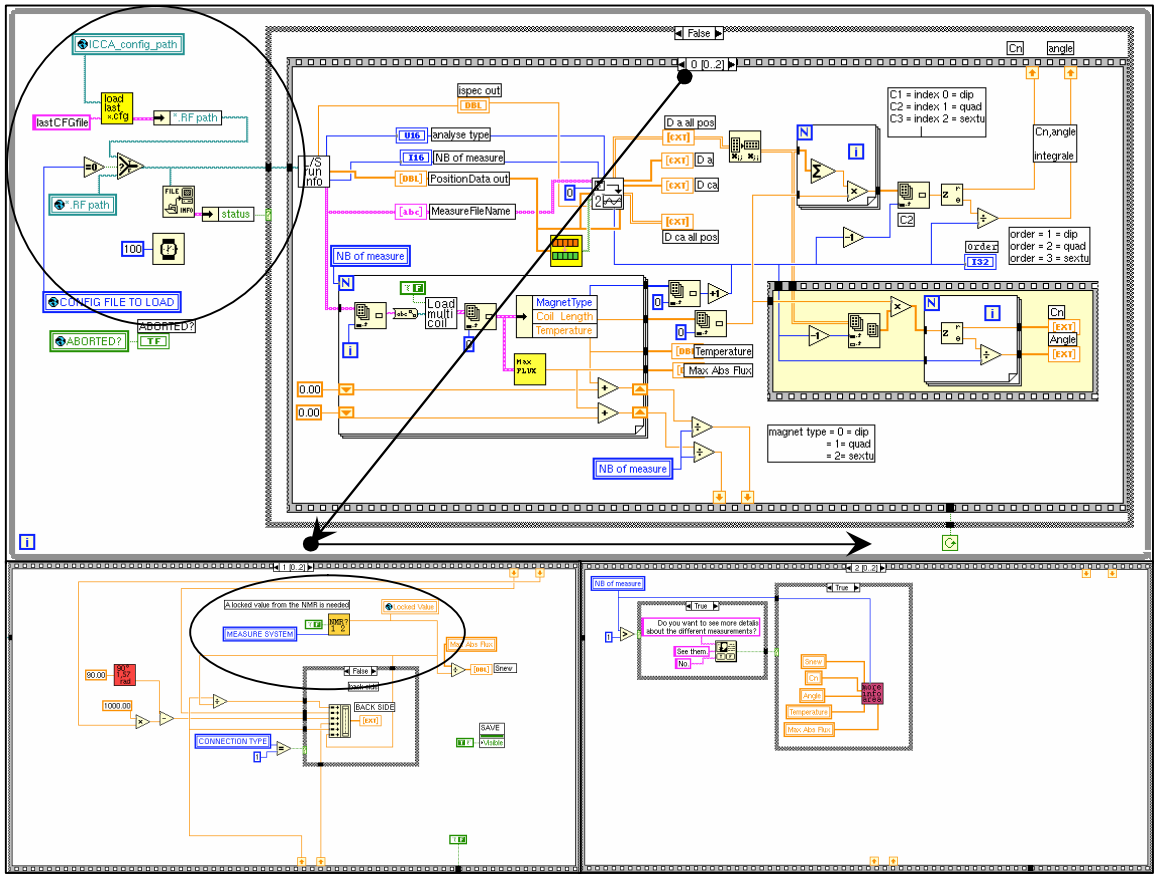


Figure 10.2: A part of the initialization frame in Area VI's diagram block

10.2.3. Parallelism VI's structure

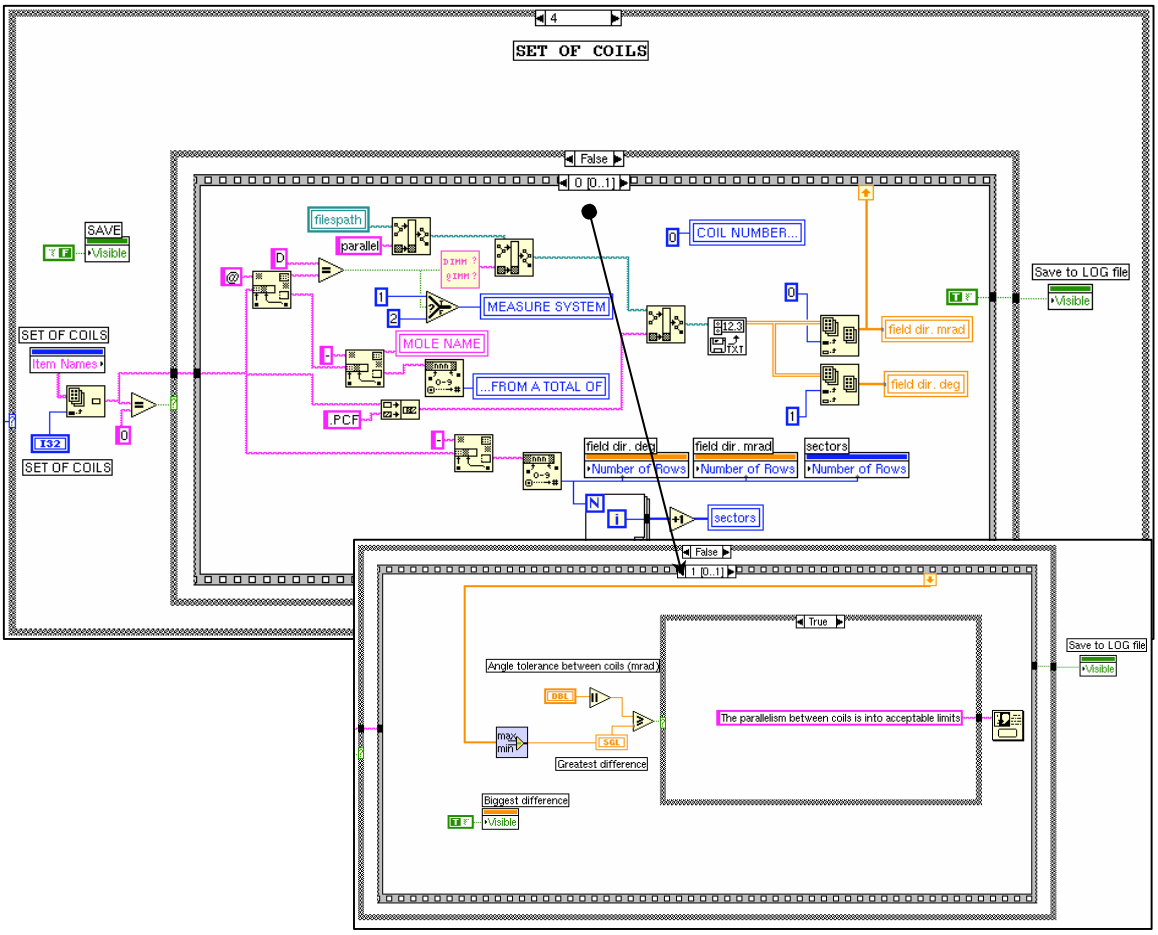


Figure 10.3: Checking the parallelism between coils in Parallelism VI

From the VI destined to the Parallelism calibration, I have found interesting to show how the names of the files are structured and how information from them is extracted in order to display it in the indicators.

When the user selects a file from the "set of coils" list, its name is detached through some filters so that to show the correct information about it: the name of the mole, the position of the coil (0 in this case since all them are selected), number of coils,

kind of measurement… and also to look for the path where this file remains. The corresponding extension is added to the name of file, then, and it is read (frame 0). In the following frame, the data loaded is treated and depending on the results, a warning message is shown.

10.2.4. LevelTRansFunction2 VI's structure

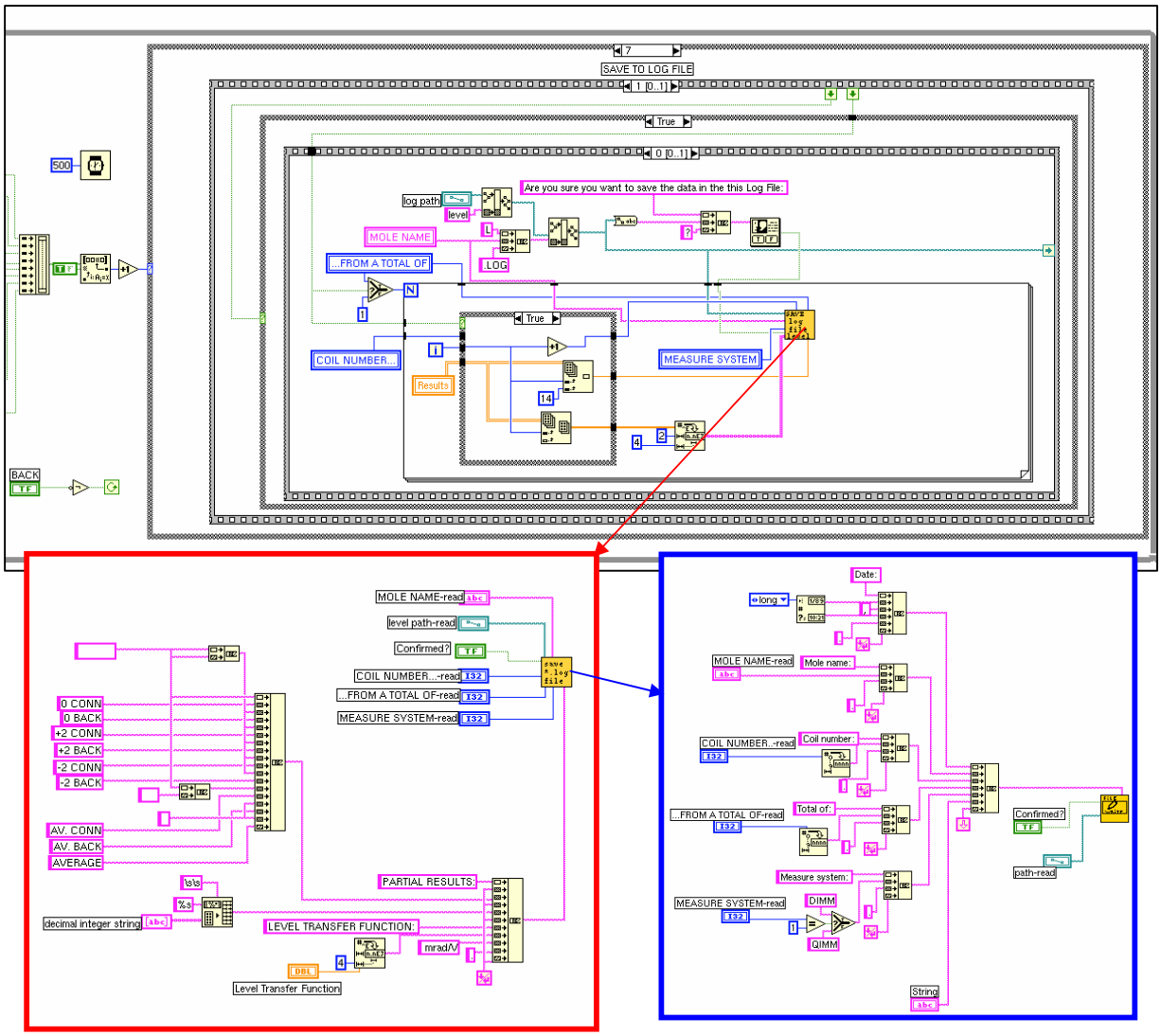


Figure 10.4: Saving data to a *.LOG file in LevelTRansFunction2 VI

This is to show how data is saved to a log file. The name of the file to be saved is formed from the different indicators that contribute with information about the mole and coils. After confirming the storage operation, the results from a table are divided into arrays (thanks to a for structure) and they are saved into a file.

10.2.5. RC_MagnetInformationsPanel VI's structure

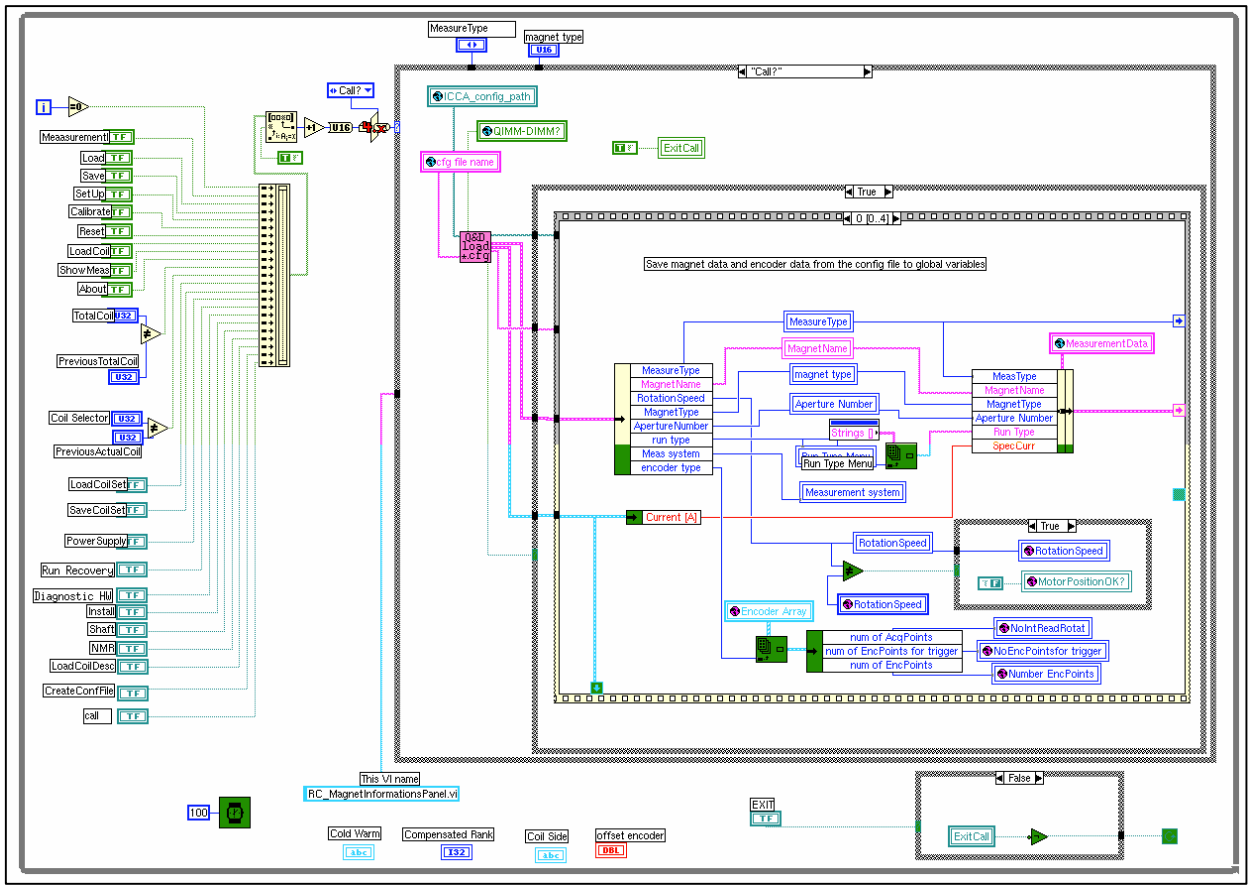


Figure 10.5: 'Call?' frame inside Rc_MagnetInformationsPanel VI

This is the structure used in the VI where the configuration file is set (visible for the user) or the measurement procedure starts (not visible for the user). A software button has been added, 'Call?', so that to take the control of the program to an

invisible state for the user but where the measurements take place automatically and all the information is correctly passed.

In the picture above, information from a file is recovered and displayed in some indicators and some global variables are initialized to start the measurement.

10.2.6. ICCA_LevelMotor VI's structure

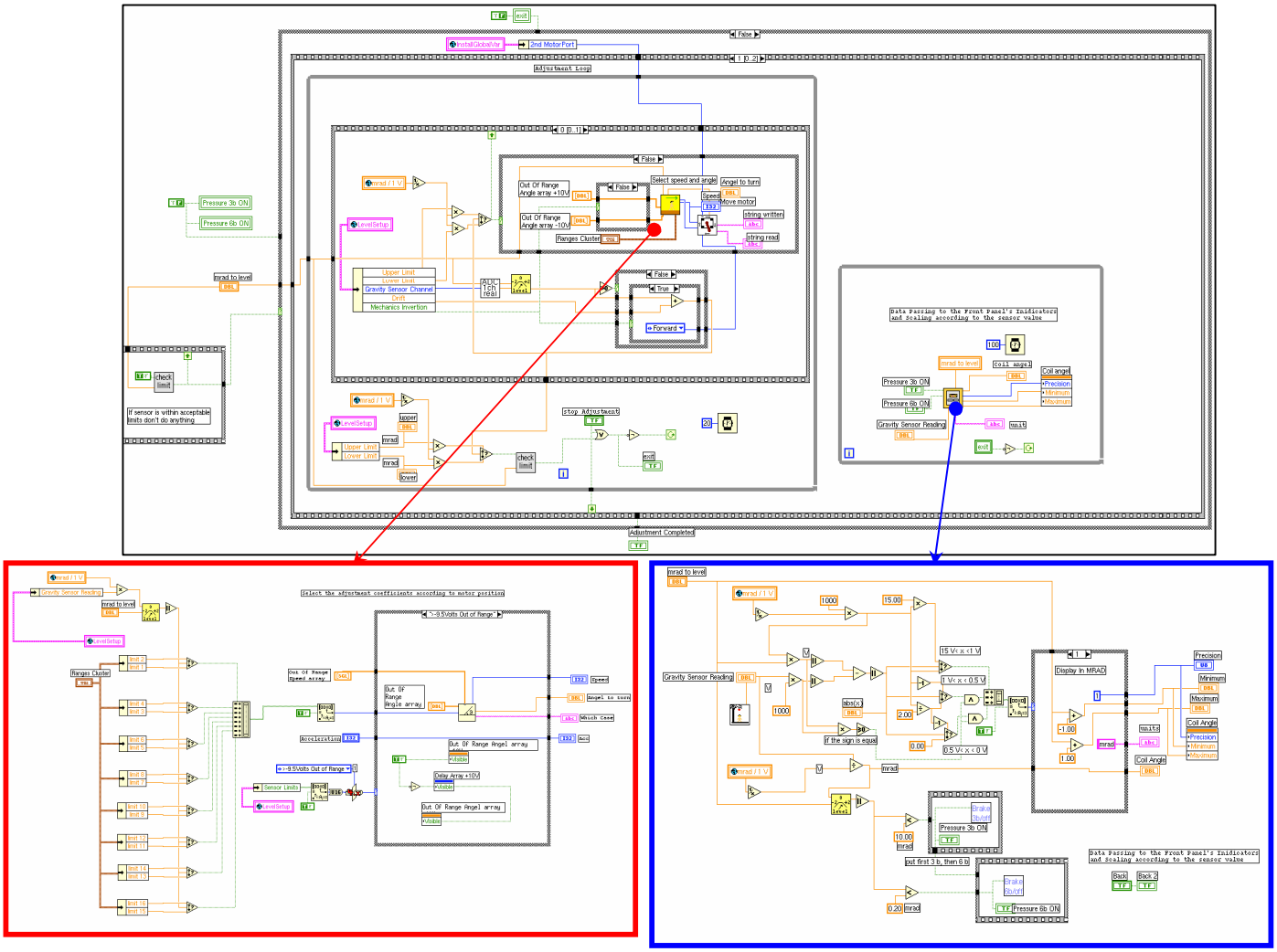


Figure 10.6: Part of the block diagram for the levelling motor control

This is the most interesting part of the VI that controls the levelling motor. The structure is the following: The levelling motor turns the coils towards the selected value (0, +2 or –2 mrad) with a concrete speed, acceleration, and angle value depending on the absolute difference to the goal (red square). After being moved, the angle is read from the ADC card (tilt sensor) and it is checked if it is into acceptable limits. If it is not like this, the motor moves again depending on the new difference to the goal. Meanwhile, the data is updated in the front panel (blue square). Once the mole level is between acceptable limits, the brakes are set.

10.2.7. RC_MakeMeasureSaclay VI's structure

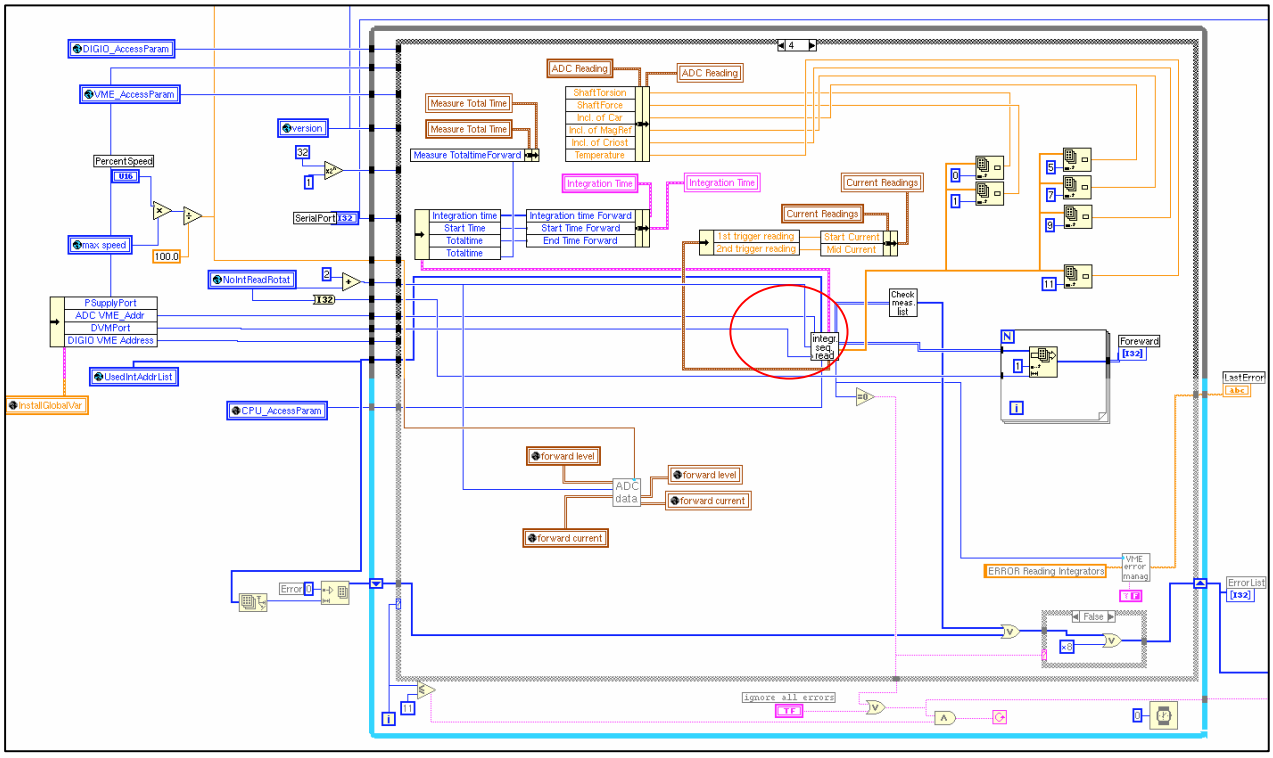


Figure 10.7: Data acquisition from integrators.

This is the most critical part of the whole program. It is when the SUN workstation polls the integrators in order to read their values in Real Time. It is into the circled VI where this is done.

10.2.8. RC_DisplayMeasurePanel VI's structure

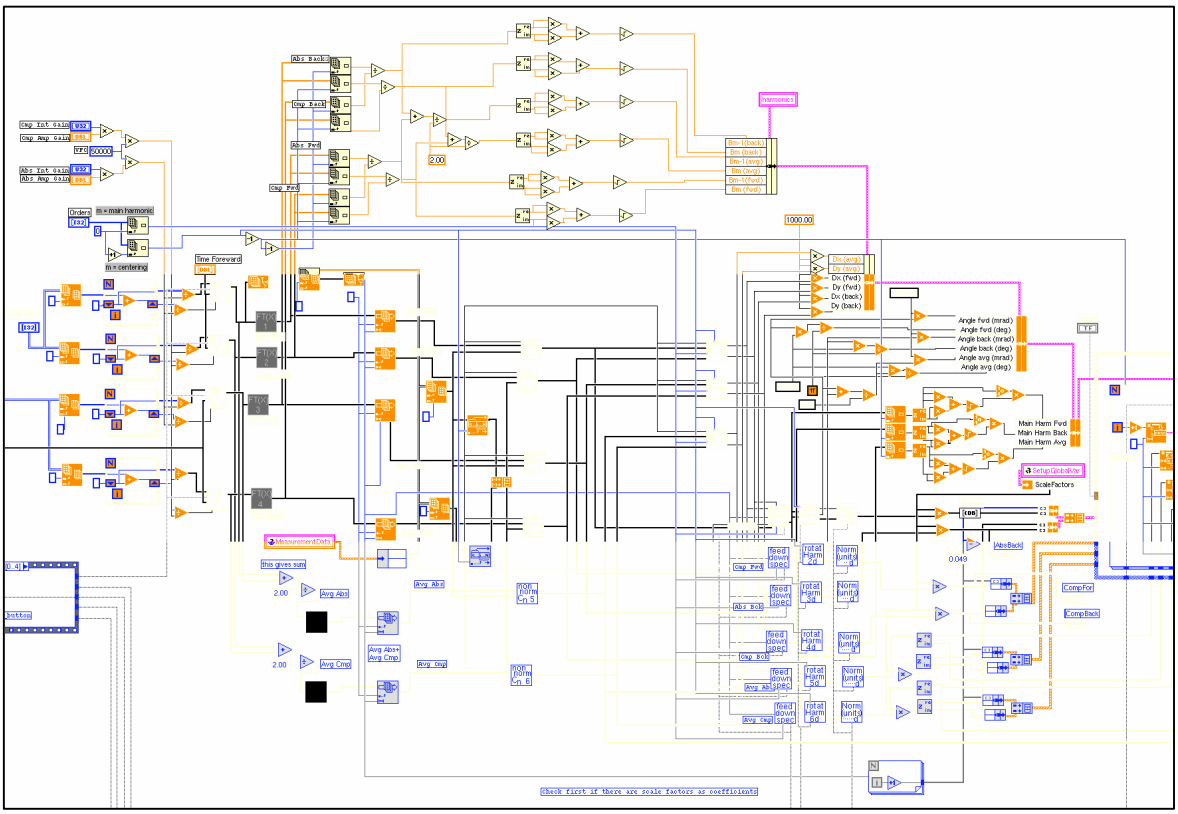


Figure 10.8: Part of the code of Harmonics.vi

To conclude, here it is a VI destined for analysis. This block diagrams is the result of the standard procedure to achieve normalized harmonics, explained in chapter 5 "Standard Analysis of Raw Data".

10.3 HISTORY OF CHANGES. ICCAchange.txt

26-6-2001 Adriaan

Avec 3 s. avant le premier point, tous les points sont mesurer correctement.
Avec 2 s. avant le premier point, le deuxieme point est blanc (saute).
Avec 4 s. avant le premier point, le premier point est blanc (saute).

Q1: quel temps est necessaire avant un point (ou le premier point) pour qu'il prend la polaritee demandee en compte?

Q2: Ou est defini ce temps?

Peut etre il faut toujours rajouter ce temps avant chaque serie de mesures.

Le PS_control.llb/getPolarity.vi ne pilote pas le Serial-GPIB/Bus-GPIB entree. On appelle directement le GPIB_Write_(Bus_or_Port).vi tandit que dans InitPS, ChangeCurrent et ChangePolarity on utilise le PS_control.llb/writeGPIB.vi qui tiens compte du choix d'interface.
Dans writeGPIB.vi j'ai change le Serial-GPIB/Bus-GPIB de control (initialement prevu) dans un indicateur.

J'ai rajoute le test sur le choix d'interface dans getPolarity.vi.

Dans user.lib/GPIB_Read_(Bus_or_Port).vi le byte count dans la lecture n'a pas ete fixe. J'ai rajouter une conversion string-nombre pour convertir le Buffer_Size dans byte count. Ceci est a controler dans les autres librairies avec le GPIB-Serial.

Meme avec ces corrections le getPolarity.vi ne marche pas.
La commande est N2, suivi d'un x, mais la reponse est toujours "courant positif". Le code retourne est 1010000, et on teste le 5eme bit (de gauche) 0 ou 1. On compte 0 le premier. Est-ce qu'il y a un probleme avec cette alim?
La commande N0 donne le voltage (toujours +)
La commande N1 donne le courant (toujours +)
La commande N2 donne le code 1010000
La commande N3 donne +60
La commande N4 donne +20

La commande N5 donne IB40 V1.30
La commande N6 donne 10807012

In changePolarity.vi dans la sequence 5 il y a un test en boucle si le courant est dans la limite de 0.01 de la valeur demande. Mais il n'y a pas de time-out, ni message d'erreur si cette condition ne peut pas etre remplis. Une erreur sur l'ADC ou l'alim peut faire tourner cette boucle pour toujours.
Il faut changer ! (J'ai rajoute un graph pour voir la montee du courant).

On a supprime le test sur getPolarite dans RC_PowerSupplyControlSaclay.vi mais il est necessaire parce que si on appelle dans chaque verification le changePolarity le courant est mis a zero avant de le remettre sur la bonne valeur. Il faut ou obtenir la polarite du ADC (si l'alim ne la donne pas) ou le faire a l'interieur de changePolarity.

27-6-2001

In initPS.vi seq 0 we should first test which interface (Serial/GPIB) before initialising any port.

On the front panel of changePolarity.vi I have added the GPIB address control. This should become an input and be driven from the callers OR we should use the global variable defining the power supply GPIB address.

29-6-2001

In changePolarity.vi we have added a global RC_PS_Polarity.glb this memorises which polarity we set
In getPolarity.vi we have added a switch to take the polarity from this global or from the power supply. Default is from the global.
We have put back the test on getPolarite dans RC_PowerSupplyControlSaclay.vi which is needed because the current is being put to zero before putting it to the required value.
Vi's changed to give more info through indicators:
Motor one acc.vi
LevelMotorControl.vi
LevelMotor.vi
motorAdjustmentPanelNewModified.vi

16-11-2001

In the changePolarity.vi frame 5 the delay in the for loop was set to 200 ms. This is too short to reach stable current for the measurement. I have increased it to 500 ms. But I had to increase the number of iterations (N=5 to 12) to get a stable current. This is using the supply Fug NTN1400 M-70. I have made the N loops a control so it can be adjusted if necessary without stopping the program.

The getPolarity has been changed to make it execute faster when we get polarity from memory. A case just for that. Previously the supply was interrogated but then the answer ignored when the switch was in "from memory". This is time consuming (6 to 7 seconds, the way it was done).

****

15-2-2002 Adriaan

On sunmms19 the serial extension software is not installed.
The admintasks don't set the priviliges correctly for this machine (paths to be changed).
The MMP software has been copied from sunmms1.
The nonvxi table has been copied from sunmms1.
The Init4SUN.vi has been copied from sunmms18.
We could include some improvements here that we have made on the sunmms18.

11-3-2002 Adriaan

On sunmms21 a init error on serial port occurred (error 37) because the two ports on the machine were not set to read/write for all users.
The admintasks don't set the priviliges correctly. Paths should be changed for the two machine ports. They are on /devices/pci@1f,0/isa@7/
I issued the command
chmod 666 *,cu
in the above mentioned directory and all works fine. Magnus should have a look at the admintasks script.

25-06-02 Hubert

Load_HarmMaxMin.vi created & saved in Disp.llb. Used to load the "Harm-MaxMin.cfg" file (from the config folder), through the "RC_ZoomMP.vi", which is used to display the harmonics of the 5 positions.

28-06-02 Peter

new_changePolarity.vi : now used in place of "change_Polarity.vi":
frame 0 : call to "new_changeCurrent.vi:
frame 3 : command "x" send to execute the polarity change
frame 4 : waining time = 1sec
frame 5 : call to "new_changeCurrent.vi:

new_changeCurrent.vi : now used in place of "changeCurrent.vi":
loop 0 : command "F1" to enable output
loop 1 : command "u..."
loop 2 : command "i..."
loop 3 : command "x" to execute the previous commands

02/07/02 Hubert

Rc_NewFeed-down Corr_spec.vi : correction du signe pilote par "Magnet order" en case = TRUE. Maintenant on * toujours par +1. A verifier par des analyse de VR.

24 07 02 Hubert
Modification in "motorAdjustmentPanelNewModified.vi" to manage the both 3b & 6b brakes.

01/08/02 Hubert

RC_HarmonicPart3.vi : CenterLocalization_new.vi was present but not connected. Now has been connected & Center.._1.vi has been removed.

27-09-02
New_changePolarity.vi :"N loop" has been set by default to 5 (before was 12).

04-10-02 Hubert & Peter
Function to put the rotating coil motor in the start position has been removed.

"Test Coil Start Position.vi" created to put the coil motor in the start pos, and called from "RC_SetupPanelm.vi".

RC_Brake_3b.vi : modified to set or reset this brake without modifing the setting of the others.
RC_Brake_6b.vi : the same.

RC_RemoveAllBrakes.vi : created to remove all the brakes, and called as replacement of the call to Brake_3b or Brake_6b.

motorAdjustementPanelNewModified.vi : sequence added on the left:
frame 0 = "check limit"
frame 1 = remove brake-3b if out of limit

Main case = false modified: frame 1 of the sequence, while loop on the right:
To compare the ADC reading of the tilt sensor, with the 10 mrad & 0.5 mrad values, the output of the ADC is * 1000 and / 600.
Then in the case:
0 = this value is put in "coil angel"
1 = this value is put in "coil angel"
2 = this value is * 1000, then put in "coil angel"

Motor Control.vi :Acc set to 15 (was 100).

Init Motor.vi : added in "make measure.vi" sequence "init"

Mspecpanel.vi : just before the call to "level.vi" (measurement case) brake 3b set to ON.

21-05-2003 Hubert

The RC_MDISP.llb of the MMP_560 has been copyed in the MMP_562 application. This will fit the request of Vittorio (19-05-2003), to have the MMP_560 analysis + all the modifications done for the brakes control of the MMP_562.

This modification generate the MMP_563 release.

26-05-03 Hubert

motorAdjustmentPanelNewModified.vi:
FALSE, seq 2 (0-2), FALSE, WHILE loop:absolute value function before the "coil angel" local variable has been removed to have an indication via the arrow related to the sign of the angle value.

FALSE, seq 1 (0-2), WHILE loop on the right: a selector has been added to put the normal value or the negated one according to the sign of the value of the gravity sensor (via AD), on the "coil angel" local variable selected.

++

MMP MODIFICATIONS FOR ICCA PROJECT

09-07-03 Ricardo

RC_MagnetInformationsPanel.vi

In the front panel, a new control has been added: "measurement system" with which we select the kind of system the calibration is going to be performed. Depending on the selection, the communication with the Teslameter is one or other so, before accessing this vi, a warning message is showed (so that to be sure that a different choice than "none" is selected).

NMR_teslameter.vi has been completely substituted by NMR_Panel.vi in case called "NMR PANEL" and in RC_DisplayMeasurePanel.vi. The new release has got an input: Communications parameters and two outputs: list of values and display. Moreover, a new global variable to save the locked value has been created. This global value is essential to calculate the correct coil area in its calibration.

With this new release it is now allowed to communicate to the Teslameter by three different vias: GPIB, Serial Port or Serial-GPIB (although this last is not still properly functioning) depending on the type of measurement it is going to be done (QIMM or DIMM). Of course, the NMR_READ.vi and the NMR_WRITE.vi have also been changed. So, RC_CalibMagnet.vi has also been modified because of this.

"Measurement Type" control has been added one more item. A default, non-used one (Index=2), so that to force users to choose an correct option each time a measurement is done or a config file is saved.

"Magnet type" control has been reduced in 4 choices (to maintain the correspondence to the global variable Measurement Data): Dipole, quadripole, sextupole and none (this last time inserted for the same reason than the previous parameter).

Case MEASUREMENT:
Some cases have been put in just one (case 3) because all them are deeply related --> messages to the user informing that something is not properly set. It has also been added three new sub cases (into case 3) in which a message is shown in case the measurement system, the measure type or the magnet type are not selected. If some of the warning messages are shown, the measurement execution is not going to be achieved. That way it is assured that main settings are correctly selected.

Case Magnet Power Supply:
powerSupplyPanel.vi has been modified by connecting a string control, GPIB_address, to all the subvi that need it. GPIB_Write has been modified in the same way.

15-07-03 Ricardo

RC_MagnetInformationPanel.vi

-In the front panel, a new control has been added. It is only visible when the MMP application is selected from the ICCA Main Front Panel (Index.vi). It is

used for creating a Configuration File (*.cfg) where all the information needed concernig to the coil parameters is stored. It must be assured that all the parameters saved are correct and the file names refers to a correct file before creating it:

CASE "Measurement":
Some changes has been inserted. Measure type and Magnet type variables are located outside the sequence structure to reduce the number of local variables.

FRAME 0: Remains the same.

FRAME 1: Checks if measurement parameters are properly selected and the user has not taken the default values. Warnings are shown if proceeds. Unless all the parameters are selected properly, the rest of he code is not going to be executed. Before the modification, all the global variables were updated and then they were checked. That way, unnecessary operations are not taking place.

FRAME 2: Checks if all coils are full configured if no error in frame 1. Otherwise integrators are reset (old 4th frame).

FRAME 3: If no problems in the previous frames, parameters common to all coils are saved in global variables (old 2nd frame).

FRAME 4: If no problems in the previous frames, rotation speed, motorpositionOK?, UsedIntAddressList and UsedIntGainList are updated. (old frame 1 with the peculiarity of adding a none Measure Type case -just to respect the number of choices of the variable but unnecessary because it has been checked earlier and there is no way to entry in this part of code-)

FRAME 5: Remains the same.

FRAME 6: Remains the same if no errors earlier.

23-07-03 Ricardo

RC_MagnetInformationPanel.vi

CASE "Create Config File":

FRAME 0: Check that the CoilSetName refers to a correct, existing file.

FRAME 1: Check that measure parameters are properly selected (no default vales).

FRAME 2: First part of the file is saved. RC_MeasureSpecSaclay.vi is called with input "caller"=2. Value that drives the .vi to a suitable ICCA panel (to save the second part of the config file).

CASE: "CALL?":
Also, another software control (never visible for users) has been added. It is called "call?". This is to entry in the MMP application in a remote mode, that does not allow any interaction with the user. The measurement is anyway achieved.
The config file selected by the user is loaded only if it really exists:

FRAME 0: Magnet data and encoder data is saved in global variables.

FRAME 1: Coil data is saved in a global variable by loading by means of the coil_set_name parameter.

FRAME 2: Integrator addresses are saved in global variables depending on measure type.

FRAME 3: Here it is called the RC_MeasureSpecPanelSaclay.vi where the levelling takes place.

FRAME 4: After the levelling and the measurement itself, RC_DisplayMeasurePanel.vi is called. The format of *.CFG files are the following:

"S"@"mole_name"-COIL"X".cfg
"S"=D if DIMM S=Q if QIMM;
"X"=number of the coil to be measured: 1,2,3,4 or 5;

04-08-03 Ricardo

RC_MeasureSpecPanelSaclay.vi

-As it has been done in RC_MagnetInformationPanel.vi, a control related to the creation of the configuration file has been inserted. It is not visible unless the input "caller" is equal to 2, that means, after saving the first block of the configuration file.

"INITIALIZATIONS":
CreateConfigFile's attribute node set to False so that no to be seen. Just set to true in the concret place.

'ICCA_LEVEL?' --> global variable always set to False in order to not modify the normal execution of the vi. It is only set to True when, in the ICCA program, it is wanted to level to a different angle than 0 mrad. Then, as it expected, the levelling of the coil is not taking place reached this point because the selected levelling of the coil is already done (from the ICCA program) .

NEW frame created: Caller=2 -->

FRAME 2: Only the interesting parameters for the measurement (to be saved in the 2nd part of the file) are visible. The rest
is set to non-visible.

NO BUTTONS:
Global variable CALL?.

FALSE: Drives to the normal execution as it has been up to the moment.

TRUE: Means we are performing the measurement in remote mode.

FRAME 0: SpecP parameters are saved in global variables. And Cycle Data if proceeds.

FRAME 1: RC_MakeMeasureSaclay.vi is called. Measure File Name is saved in a global variable, too.

FRAME 2: Since the measurement is finished, the VI is forced to be closed.

"Create_Conf_file":
This point of the project is reached when it is wanted to save the remaining parameters (2nd block) for the configuration file.

FRAME 0: If Current Cycle is selected, it is assured that the cycle name really exists and corresponds to a cycle file.

FRAME 1: Current type, cycle name, current mode and Number of measurements selected are saved in the config file previously created.
Since the creation of config files, measurement in remote mode can be performed (useful in the ICCA application).

23-09-03 Ricardo

RC_MakeMeasureSacalay.vi

A new ICCA's global variable (indicator) has been added in the frame "New measure set", case "True". With it, the whole path (included file) of the last Run File generated is stored. That way, it can be loaded in ICCA's project in a very simple way to treat the information inside (to calculate the new surface).

29-09-03 Ricardo

RC_LoadSaveCoilCoefset.vi

Case "Save".

The name of the *.CCS file must be saved automatically with the following format: coilname.CCS instead of allowing the user to save this with the name he/she wants. That way, from ICCA's project (while calculating new coil areas), when the user selects a *.cfg file to be loaded, the *.CCS tied can be easily loaded.

14-10-03 Ricardo

RC_MagnetInformation_Save.vi and RC_MagnetInformation_Load.vi

In "Load" and "Save" cases in the main loop, the cluster TempMagnetData has been added one more variable: Measurement System (none, Dimm or Qimm system are the possible choices).

RC_CoilSet_Load.vi

This vi was created to get information saved from a *.CST file (composed by a set of *.txt files related to each sector of the coil) and then to save it to the global variable "CoilSetData". BUT if the user wanted lo load this information for changing (as example) one parameter in a concrete *.txt file and then save the *.CST file again it would be impossible since all the information is not reachable on the front panel. So, an output path array with the name of all the *.txt files related to the *.CST file has been added.

RC_MagnetInformation_Load.vi

As in the previous case, this vi was created to load information stored in *.RCD files (also composed by a set of *.txt files AND the "measurement parameters"). This information is useful to update the global variable CoilSetData and to show part of the information... BUT there is no way to change them because the *.txt files are not reachable. An output path array with the name of all the *.txt files related to the *.RCD file has been added.

RC_SaveCoilFile.vi

The name of the *.txt file is not anymore selected by the user but its format now is the following: "coil name"-SECT"Sector Number".txt

11-11-2003 Ricardo

readcurrent.vi replaced by ReadcurrentGPIB.vi

As in the calibration minirack it is not foreseen to use an ADC card for reading the current from the Power Supply, a new vi that reads it through the GPIB bus must replace the one that acquires the current value via ADC card:
- the use of readcurrent.vi is replaced, by a case structure, by ReadCurrentGPIB.vi. This last vi takes into account which is the current type selected in the actual measurement. Since we cannot read the current from the power supply if it is selected "manual control" in current type (physical selector on the power supply avoid this), the output gets the value from the Speccurrent in this concrete case.

ICCAlevelsetup.cfg

The ranges used nowadays in the QIMM system for the levelling are not correct. Peter Galbraith said that he gave a bad conversion from Volts to mRad (1.67). The new factor is 1.454:
Taking on account that 6 V --> 0.5 deg it is easily reachable the following conversions:
1 V -> 1.45444 mrad and 0.6875 V -> 1 mrad

For this reason, a new config file with the new range values, new speeds, new angles to turn... for levelling to be loaded at the beginning of the program and

to be stored in the global variable LevelSetup has been created: ICCAlevelsetup.cfg

MainICCA.vi

In frame number 4, the new file to be loaded concerning the levelling is ICCAlevelsetup.cfg.

RC_MeasureSpecPanelSaclay.vi

"No buttons" True Case (Remote mode)

Instead of 3 frames, there are 5:
FRAME 0 and 1: The global variable ProfEditorCycleData is updated with the values from the configuration file (Spec Parameters).
FRAME 2: The global variable MeasPSData is also updated from Spec Parameters.
FRAME 3: Independently of the current type selected (manual or set via GPIB, constant), the current value is updated in the indicator. (value extracted from the Spec current by the user in manual mode or directly read from the Power Supply in constant or cycle).
FRAME 4: The levelling takes place:

FRAME 0: FindZeroMotor.vi is called.

FRAME 1: Put the brakes on (3 bars).

FRAME 2: Depending if the levelling is called from the LevelTRansFunction2.vi (in Index.vi) or not, the level goal is the selected one from this vi or 0 mRad as it has always been. In case it is been dealing with a DIMM system and the level goal is different by 0 mRad, a message is shown warning the user to level the mole by hand to the selected value and then click to go on. (It is done like this because not even with this software, in the DIMM system the level goal can be different of 0: Hardware limitation)
FRAME 5: MakeMeasureSaclay.vi is called after the levelling process.

ICCA_LevelMotor.vi

This is the vi that performs the levelling. It is a new version of the existing one that allows the user to level the mole to a certain mRad value, not

necessary 0 mRad. So, a yellow vi called mRadToLevel.vi has been added to create relative differences and to be able to level the mole to different values. Also note that the values to convert mRad to V and vice versa have been changed. 0.69 instead of 0.6 and 1.45 instead of 1.67.

RC_MakeMeasureSaclay.vi

The indicator's name "Current (ADC)" has been changed to "Current GPIB" (it is, more understandable).

CASE "MEASUREMENT":
In Frame 3 and 6, some code has been added: It is for reading the Tilt Sensor value just before and after each measurement and checck that all the values in the X different measurements at a time, this value is stable and there is no problems with the brakes. updateReadTiltSensor.vi stores these values in an array.

CASE "NEW MEASURE SET":
CASE "TRUE": The measurement ends.
FRAME 0: The X measurements' results that have already been made are analyzed. If the average angle difference of all of them are greater than 0.3 mRad or the Tilt Sensor value varies 0.2 mRad during the measurements (e.g.: there is a problem with the brakes) then, they (the measurements) start again before putting the brakes off. This way, the Tilt Sensor value is expected to be more stable and, hence, the average angle. AverageAngleMeas.vi calculates the average angle of the measurements. It must be said that this value is all right for vertical magnets. As it is not the case, a correction of 90 degrees (subtraction) has to be done to achieve the correct value.
FRAME 1: If these conditions are passed then
TRUE: The measurements are considered corrects and data is stored. A global variable called "*.RF path" is the one that saves the run file path with the saved files so that to recuperate it easily later in Area_2.vi (in Index.vi)
FALSE: If after three tries (3 repeated measurements) the conditions are not passed, then the process is aborted and a message is shown.

CASE "INITIALIZATION":

Some new variables, the ones related to the new Tilt Sensor and average Angle checking are initialized.

15-12-03 Ricardo

AREA.vi, LevelTransFunction2.vi, parallelism.vi
A new LED indicator has been added next to the results extracted from the measurements. This LED will warn whether the results are from aborted measurements or not.

15-01-04 Ricardo

ICCA_motorAdjustPanel.vi

Frame 2: The code inside a 'for' loop, destined to passing data to the front panel's indicators and scaling the needle according to the sensor value, has been changed and converted into a subVI called 'LevelDataToFrontPanel.vi. Now, the distance between the real and the expected level value is constantly checked if it is within absolute ranges and not from ranges depending on the 0 mrad as it was before. It has been converted into a VI because it will be used in DIMM systems when the levelling process is done by hand (and the VI will show the evolution of the levelling).

AREA.vi

When a three coils mole is used for measurements, the area values from RC_CoilCoefCalc.vi referring to this three coils are not the 1st, the 2nd and the 3rd position in 'Coil area (m2)' array as it was supposed but they are the 1st, the 3rd and the 5th, being the 2nd and the 4th equal to 0 m2. This concrete situation must be corrected with the creation of the vi called 3coils.vi that controls and reconstructs the array so that to respect this format. It is being used each time these area values are recovered from or overwritten to *.CCS files and the mole contains three coils.

Index.vi

The first time a measurement is carried out with a mole, it is EXTREMELY important that the control 'TOTAL OF COILS' on the front panel is correctly

set with the total number of coils inside the mole. As it is easily forgettable, a new VI has been created: 1molepercoil.vi. With it, if this control is equal to one, value by-default, before the measurement takes place, a message warns the user.

RC_MakeMeasureSaclay.vi

This error inside VMExreceive_LV.vi: "A VME access error occurred, likely cause: an integrator did not respond. Please abort the current measurement, exit the program and check the integrators before starting again" is sometimes shown when a measurement (forward or backward) has not been able to start because of a timeout error (integrator did not respond). A new software indicator has been created that will indicate if the results achieved (magnetic field angle) are extracted from abort or bad measurements. This, that is not visible for the user up to the moment, will be linked to the LED AREA.vi, LevelTransFunction2.vi and parallelism.vi. That way, these LED will warn not only if the information extracted come from aborted measurement but also from this source of error.

Index.vi

If the last measurements failed (aborted or any other error source), the indicator 'LAST CONFIG FILE LOADED' will show the word 'ERROR' that will mean that it is not worthy to recover these data since they are bad ones.
05-02-04 Ricardo

NMR_Panel_2.vi

In order to achieve an accurate magnetic field value, instead of using the last locked value read for the calcultaion of the coil surfaces, the average of as many locked values as the user wants will be used. For this purpose there are two new numeric indicators: the number of locked values read since the actual moment and the average of them.

Index.vi

A new subVI called scanmolename.vi has been created. Its function is to search for mole's name in a string (from a file, normally) and with a concret format

('name of the mole'+'TAB'). It is used when updating info from the cfg file (Frame 8) and inside checkNumbSectfromCoilname.vi (Frame 0).

Remot_call.glb

The convertion between Volts and mRad is now being used as a global variable (called mrad/1V) instead of using constant values as it was up to this moment.

18-02-04 Ricardo

RC_MakeMeasureSaclay.vi

Inside the frame "Measurement", in frames 3 and 7, the NMR is called to read an average field locked value for each measurement when coil surfaces are wanted to calculate. That is to say, there will be an average magnetic field value from the Teslameter at the beginning and at the end of each measurement. Then, the average will be calculated. These values will be stored in the global array AvNMRValue.

NMR_Panel_3.vi

A new update from NMR_Panel_2.vi that will substitute it: There are three new controls with which the user can select when to start, stop or reset the acquisition of the field values. That way, the user can 'manually' get the locked value and then acquire some values to calculate the average.

RC_LoadSaveMeasRestrictions.vi

This VI has been created. It is used in MainICCA.vi, frame 3, to load the restrictions to be set in the measurements and to save them into the global array MeasRestrictions. It is composed of three elements:
1st -> angle biggest difference between coils
2nd -> tilt sensor biggest difference between the beginning and the end of one measurement.
3rd -> tilt sensor biggest difference between the beginning and the end of the whole measurements.
That way, the restrictions are not anymore constants inside the block diagram but they pass to be loaded from the file ICCAMeasRestrictions.cfg.

RC_CreateCoilCoef.vi

There are times that *.txt files are not well saved because the CoilCoeff table is empty in spite of being values in it. Values, that can be shown in the panel, are the ones remaining from previous *.CCS file loadings but inside the matrix variable there is nothing. To avoid this bad situation, the table gets empty everytime a *.CCS file is loaded and a warning message is shown at the time of saving *.txt files if the coeff table is empty.

10.4 HISTORY OF RELEASES. ICCArelease.txt

Project Acronym	Project full name
ICCA	Industry Coil CAlibration

Application name (tar)	Version	Date	Programmer
Short description of changes			Link to VCF
MMPMMS-050400.tar	5.5.0	27.02.2002	Adriaan
For sunmms19 quad Tesla			MMPMMSchange.txt
MMPMMS	5.6.2	28.06.2002	Hubert
For sunmms21 quad Tesla			
QIMM_563.tar	5.6.3	21.05.2003	Hubert
For sunmms19 quad ACCEL			MMPchange.txt
ICCA_300_081203.tar	300	08.12.2003	Ricardo
For sunmms15			ICCAchange.txt
ICCA_301.tar	301	18.12.2003	Ricardo
For sunmms9			ICCAchange.txt
ICCA_302_060204.tar	302	06.02.2004	Ricardo
For sunmms9			ICCAchange.txt
ICCA_303_090204.tar	303	09.02.2004	Ricardo
Before demo AT/MTM			ICCAchange.txt
ICCA_304_200204.tar	304	20.02.2004	Ricardo
More NMR lectures			ICCAchange.txt

CONCLUSIONS

ICCA system was born to become the first step in the magnetic measurements since assuring that the tools used for the verification and analysis of magnets features, the coils inside the moles, is an essential, basic procedure.

The accuracy, reliability and reproducibility of the values achieved in all the procedures are guaranteed:

- It has been experimentally tested that the mole is always leveled within a reasonable (and reduced with respect to previous operations) range: ±30 mrad.
- Due to lasts improvements in the VI that controls the NMR, different lectures of the magnetic field before and after each measurement can be achieved after having assured that the lecture is stable. Doing like this, the final, average value will have a high accuracy for the calculation of the coil surfaces
- The addition of some restrictions once the measurements are finished, very much increases the reliability and reproducibility of them since they are repeated as long as the field angle and the tilt lecture are stable in the whole set of measurements. This procedure also allows detecting damaged or worn away brakes inside the moles.

The calibration program is far to be a closed one, many other applications as the existing ones can be easily added, since its expansion has been taken into account during the structure design's stage of the program. The fact of having used a program for its development with the features of LabVIEW minimizes time and efforts at the time of updates. By the way, specifications for a new calibration measurement, that will allow the calculation of the magnet's inclination, have been recently sent to us.

For achieving a friendly environment for users with which managing this program for calibration (that allows them escape from the complexity of the inner code) most of the panels have been designed in a standard, intuitive way. The dealing of them is much easier understandable due to that format.

The future place for the management of this system is not clear, yet. The first idea was to install the software in the different industries that require it as it has been done with many other systems. However, due to the criticism and importance of the calibration system, some other possibilities are being studied such as: using this system only at CERN and by specialized people from CERN or using it in the industries but only by specialized people from CERN that periodically should go there for this purpose. Nowadays, AT/MTM group is aware of the existence of this system therefore it can be said that the system is *under test*. Then, we are waiting for their approval and/or a list of final modifications or improvements that were not specified at the beginning but may be interesting and useful for the users at this point.

Finally, I have to express my feelings of pride and happiness because, after around nine months of work, the calibration bench, software and documentation are available and ready to be handled.

LIST OF APPENDIX

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APPENDIX 1

SPÉCIFICATION FONCTIONELLE DE LA CALIBRATION PÉRIODIQUE DES TAUPES MAGNÉTIQUES

PRINCIPE

Mesurer périodiquement les caractéristiques des taupes pour garantir la précision des mesures et suivre leur évolution.

PARAMÈTRES DÉFINISSANTS UNE TAUPE:

1.	Surface des bobines (+ écarts à la bobine "mesure")	(m^2 et %o)
2.	Parallélisme entre bobines (écarts à la bobine "mesure")	(mrad)
3.	Rayons de rotation des bobines	(mm)
4.	Décalage dans le plan des bobines	(mm)
5.	Décalage perpendiculaire au plan des bobines	(mm)
6.	Décalage de zéro du niveau	(mrad)
7.	Fonction de transfert du niveau	(mrad/V)

PARAMÈTRES MESURÉS LORS DE LA CALIBRATION PÉRIODIQUE:

(1) et (6)

(2) peut être mesuré si l'on peut orienter les bobines à un angle fixe $\theta = 0 \pm 2$ mrad.

(7) peut être mesuré si l'on peut régler le niveau de la taupe à des valeurs différentes de zéro (±2 mrad, par exemple)

Les paramètres (3), (4) et (5) sont mesurés lors de la calibration de la taupe au CERN, dans le quadripôle de référence. L'expérience montre une stabilité de ces paramètres géométriques de l'ordre de 5 microns dans le plan des bobines (paramètres (3) et (4)) et de l'ordre de 20 microns perpendiculairement à ce plan (paramètre (5)). Des valeurs un peu supérieures peuvent être trouvées en cas de dé-collage puis re-collage de la

taupe. Ces opérations ne peuvent se faire qu'en 230 et sont nécessairement suivies d'une re-calibration complète en I8.

SYSTÈME DE CALIBRATION

Il consiste en :

- un aimant dipôle en "U", suffisamment long (880 mm) pour que les bobines de la taupe (750 mm) soient dans un champ magnétique constant sur toute leur longueur.
- un tube inox 53/50 mm identique au tubes faisceau des aimants LHC, dans lequel la taupe est introduite pour faire les mesures.
- deux systèmes d'entraînement à deux moteurs, un pour niveler la taupe à l'angle choisi, l'autre pour tourner les bobines. Ces systèmes sont placés symétriquement de chaque côté de l'aimant pour pouvoir faire des mesures avec retournement.
- une sonde NMR proche du tube, donnant la valeur précise du champ en un point, permet de connaître la valeur de l'intégrale du champ à l'emplacement des bobines de la taupe, puisque la mesure de l'intégrale a été faite préalablement avec une autre sonde NMR.
- un petit rack électronique équipé d'une alimentation et d'un châssis de contrôle permettent l'excitation du dipôle en "U" et la sélection des bobines. Les autres fonctions de la mesure sont faites avec le rack principal. Notamment l'intégrateur

"absolu" et le contrôleur de niveau (MUPI) doivent les mêmes que ceux utilisés dans la mesure des aimants. Le logiciel doit donc pouvoir s'adapter soit sur DIMM pour les firmes dipôles soit sur le QIMM pour les firmes quadripôles.

SÉQUENCE DES OPÉRATIONS

1. Initialisation
   1.1. numéro : de la taupe, de l'intégrateur, du MUPI
   1.2. menu : taupe d'un système double (système dipôle) ou taupe d'un système simple (système quadripôle ou provisoire dipôle)
   1.3. date de la calibration
2. Mesure des surfaces des bobines (paramètre (1))
   2.1. Faire la mesure standard de la valeur absolue du champ (intégrateur "mesure" sur la bobine "mesure")
      - 3 tours dans un sens, 3 tours dans l'autre.
      - Si la surface est exacte, le champ mesuré doit être égal à celui calibré contre NMR
      - Sinon, la surface doit être corrigée et la nouvelle valeur introduite dans le tableau des paramètres de la taupe.
   2.2. Recommencer l'opération en connectant successivement l'intégrateur de la bobine "mesure" sur les autres bobines de la taupe.
3. Mesure du parallélisme des bobines
   3.1. Le codeur et le niveau de la taupe ainsi que la direction du champ et de la gravité, ne changeant pas pendant les mesures précédentes, les différences de direction du champ donnée par chaque bobine correspondent aux défauts de parallélisme entre bobine
4. Fonction de transfert du niveau
   4.1. Régler le niveau de la taupe successivement à + 5 mrad, 0 et – 5 mrad

4.2. Faire chaque fois "2.1."

4.3. Si l'orientation calculée du champ ne correspond pas à la valeur donnée par le niveau, corriger la fonction de transfert dans le tableau des paramètres de la taupe

5. Contrôle du zéro du niveau

5.1. Retourner la taupe sur l'autre position du système.

5.2. Refaire les opérations "4.1" et "4.2"

5.3. Si les directions du champ ne correspondent pas à celles trouvées dans l'opération "4", le "zéro" du niveau doit être corrigé de la demi-somme (paramètre (6)).

5.4. Une vérification doit être faite par un dérèglement calibré du nivellement de l'aimant. Ce dérèglement doit être retrouvé, avec le bon signe, sur la nouvelle orientation du champ mesurée.

APPENDIX 2.

ICCA USER'S MANUAL

ABOUT THIS MANUAL

This manual is intended to provide information about how to follow the stability of the coils inside the moles with which the value and the geometrical quality of the static magnetic field inside the magnets under test will be validated. Also, it allows the user to know all the possibilities that ICCA program offers and which are the tricks to achieve successful, fast results as well as how the information flux is passed and saved.

Since this program is based on magnetic measurements, this manual also includes information about how to make them step-by-step aided of the LabVIEW's front panels that appear while launching this application.

ORGANIZATION OF THIS MANUAL

Six different chapters compose this manual:

PANELS' DESCRIPTIONS 121

The handling of all the panels in this list is described: HOW TO START, MAIN MENU, MMP. CONFIGURATION FILE (I), CREATING COIL DESCRIPTION, MMP. CONFIGURATION FILEE (II), CYCLE EDITOR, NMR TESLAMETER, POWER SUPPLY, FIND ZERO ENCODER, LEVELING MOTOR ADJUSTMENT, MAKING MEASUREMENTS, RESULTS, DISPLAY MEASUREMENT, COIL AREA ANALYSIS, COIL PARALLELISM MEASUREMENT and LEVEL TRANSFER FUNCTION MEASUREMENT.

HOW TO MAKE MEASUREMENTS 171

A brief explanation of the procedure to make measurements in a proper way with the new software.

ICCA'S FLOW CHART 180

To have a general view of the panels and the way they are linked.

FILES' PATHS AND DISTRIBUTION 181

This is to know in which path is each file

TYPE OF FILES 182

A short description of the format of the following files and their contents: *.CFG, *.txt, *.CCS, *.LOG, *.CAL, *.TAF, *.LCF, *.PCF and *.TPF.

NEW LIBRARIES AVAILABLE 193

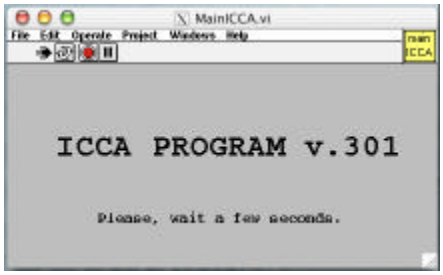
PANELS' DESCRIPTIONS

- **HOW TO START.**

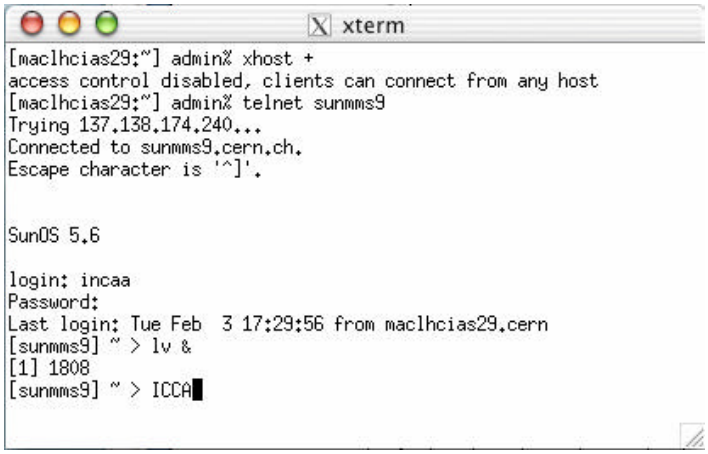
The default folder where the main VI is saved is the following:

/opt/home/incaa/ICCA301/ICCA/MainICCA.vi

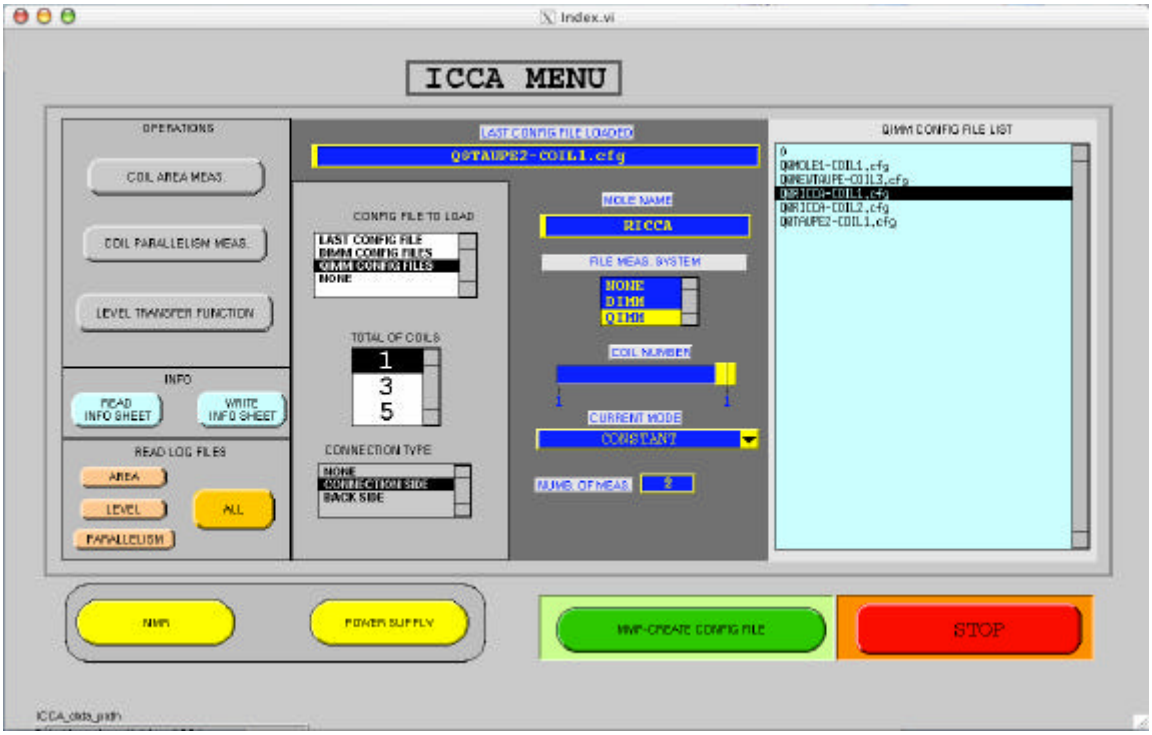
Some seconds after loading it (and its more than 400 sub VI) this panel will appear. The program can be started, then, by clicking on the run button. Doing this, the system will enter in an initialization state for a few seconds (load the necessary files and initialize the Sun and the rest of the hardware such as: Power Supply, ADC card, VME cards, motors controller…) and later, the main menu with which users are going to work will be displayed.



An *alias* for launching the application has been created. Then, typing *ICCA* the application will be opened auyomatically without the necessity to open labVIEW previously.



- **MAIN MENU.**



The list of controls and indicators in this screen are the following ones:

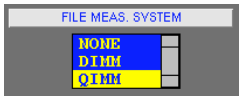
INDICATORS:

These are inserted on a grey, dark background space (at the center of the panel). They have got a yellow contour and text and a blue background. From top to bottom:

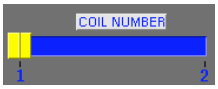
1. **LAST CONFIGURATION FILE LOADED:** Shows the name of the last file with which the measurement has been made.

2. **MOLE NAME:** Field in which the name of the mole that corresponds to the configuration file selected is shown.

3. **FILE MEASUREMENT SYSTEM:** Indicates the kind of system that must be used with the configuration file selected. It can be a QIMM or a DIMM system.



4. **COIL NUMBER:** This indicates the position that the coil to be calibrated occupies into the mole (e.g. if it is 1, it means measuring coil: E1…).



5. **CURRENT MODE:** It shows which is the type of current to be set in the power supply. It can be constant, manual or cycle.

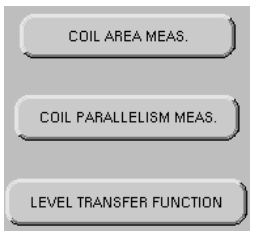
6. **NUMBER OF MEASUREMENTS:** Indicates how many measurements are going to be made.

7. **mrad LEVELED:** It is only visible if the last configuration file used is selected. It indicates which was the last leveling value.

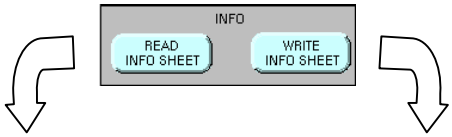
CONTROLS:

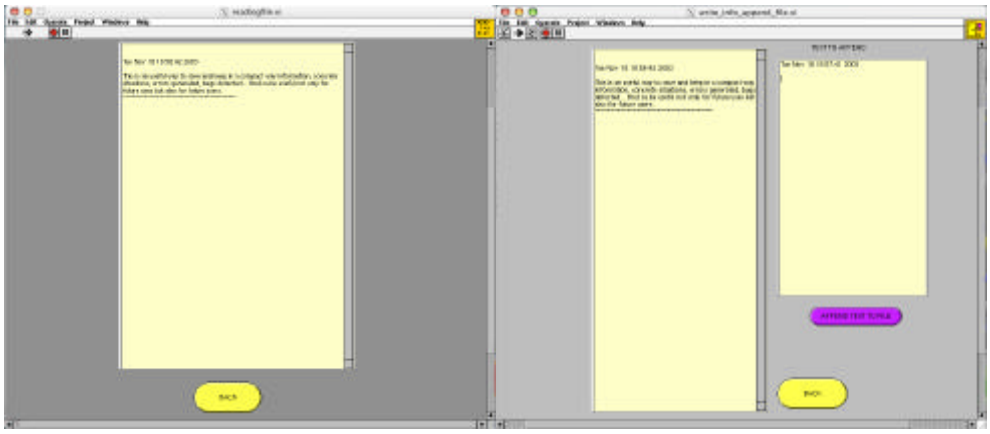
The rest of buttons are controls. From top to bottom and left to right:

1. **OPERATIONS:** These controls lead the user to three different analysis and results after the magnetic measurements.
   a. **Coil Area Measurement:** Leads the user to an analysis panel where coil areas are recalculated.
   b. **Coil Parallelism Measurement:** Leads the user to a panel where the parallelism between the coils inside the mole is checked.
   c. **Level Transfer Function:** Leads the user to a panel where information about the state of the tilt sensor inside the mole can be checked.

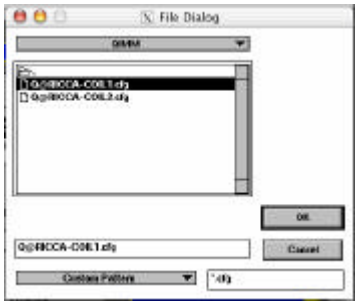


2. **INFO:** These choices allow the user to write and read a sheet with the proposal of saving punctual situations, detected bugs, special procedures, suggestions or whatever that could seem interesting for future uses and users.



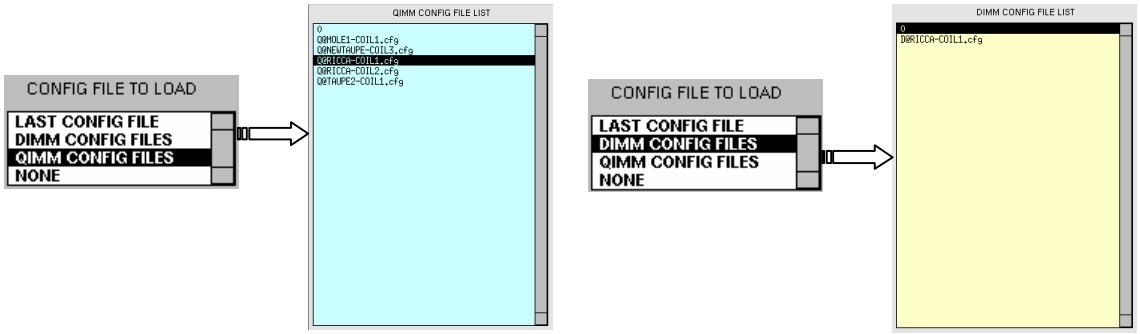


3. **READ LOG FILES:** An access to the files generated once a coil has been analyzed is open with these controls in such a way that the results are directly available without the need of going to one of the three corresponding analysis panels.

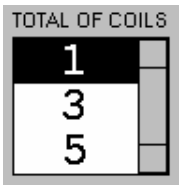


4. **CONFIG FILE TO LOAD:** With this control, one can choose between configuration files referred to a DIMM, to a QIMM system or the last one

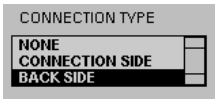
used. Note that depending on the system it is selected, a different list will appear on the right side of the screen.



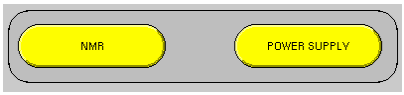
5. **TOTAL OF COILS:** This is a control to be set the first time one is working on a mole. Once it is set and the first measurement takes place it will be fixed on the value it was selected then. So, when any other configuration file related to the same mole name is selected, this parameter will not be able to be changed.



6. **CONNECTION TYPE:** This is to differentiate the position of the mole in reference to the bench. One can make a connection side or a backside measurement.



7. **NMR and POWER SUPPLY:** These control leads the user to panels in which the NMR Teslameter and the Power Supply can be respectively controlled and tested.

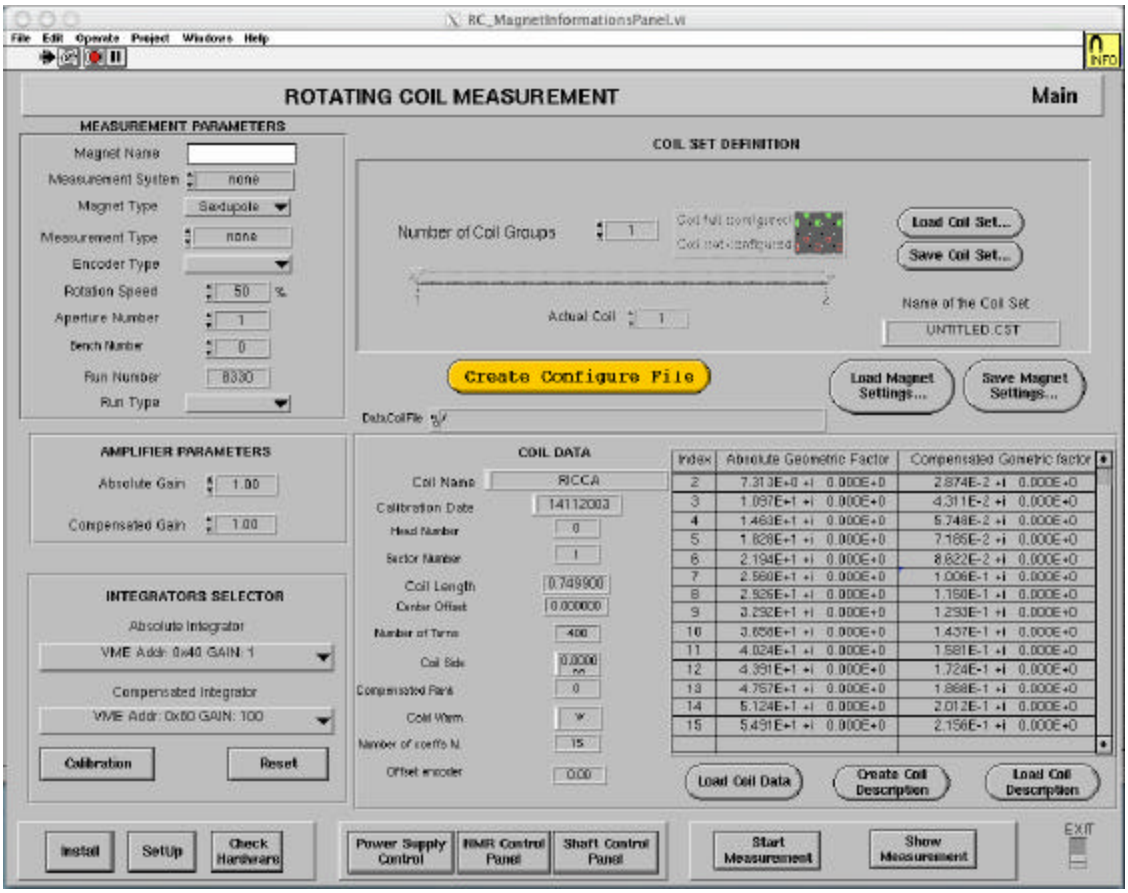


8. **CREATE CONFIG FILE:** This button allows the user to pass to a new screen, a new version of MMP, in wich the configuration file will be created.

9. **CONFIG FILE LISTS:** These are lists that store all the configuration files previously saved. Only one configuration can be selected at a time and only one list (for DIMM or QIMM) is shown at a time, as well.

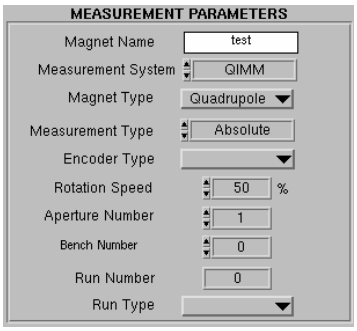
10. **STOP:** This control stops the execution of the program.

- **MMP. CONFIGURATION FILE (I).**



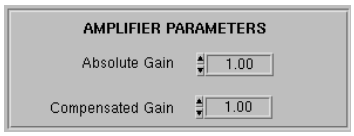
If a configuration file is needed, this is the first window in which the user deals with the creation of the first part of *.CFG files. Some new controls and indicators have been added to make it easier (new version of MMP-563). The newer ones, which must be used for creating the configuration files, and the rest, are explained below:

1. **MEASUREMENT PARAMETERS:** All the available fields must be filled in with different values than the default ones: the name of the magnet under test, its type (Dipole, Quadrupole, Sextupole…), the measurement system (QIMM or DIMM), its

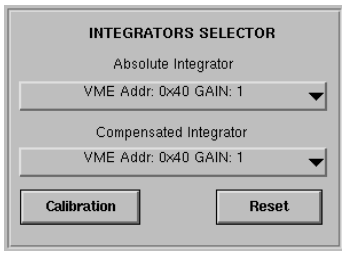


type (Absolute or Compensated), the encoder type (choose one from the existing list) and the rotation speed of the motor. The rest (the number of aperture, the bench number and the run number) are not anymore used in this version.

2. **AMPLIFIER PARAMETERS:** To select the absolute and the compensated gain. (Set to 1 by default).

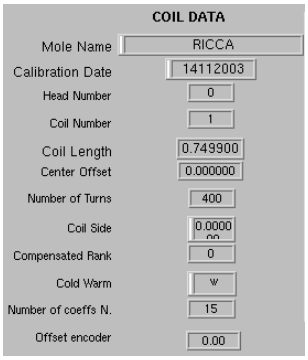


3. **INTEGRATORS SELECTOR:** Composed by two list from which it will be selected an integrator for the absolute and one more for the compensated measurement. Also, the integrators can be reset and calibrated with the corresponding controls.

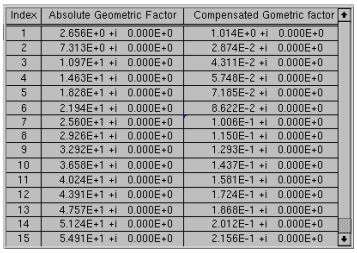


4. **COIL DATA:** This part is dedicated for parameters related to the mole and the coils inside. It is mainly composed of indicator fields, a table and three controls:

   a. Coil data indicators: Show all the parameters that describe the coil inside the mole under calibration: mole name, calibration date, the head number, coil number (inside the mole), the coil length, the number of turns, the number of coefficients extracted… All these are shown once a *.CCS file or a *.txt file is loaded.

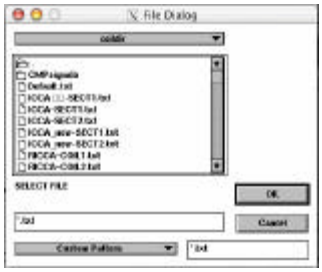


   b. Coil geometric factors' table: shows all the representative (absolute and compensated) factors of a mole, also visible when a *.CCS or *.txt file is loaded.

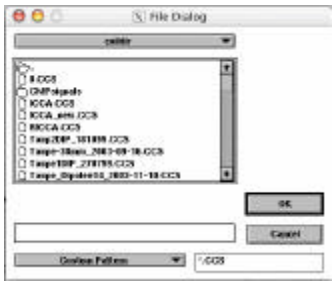


Index	Absolute Geometric Factor	Compensated Gometric factor
1	2.656E+0 +i 0.000E+0	1.014E+0 +i 0.000E+0
2	7.313E+0 +i 0.000E+0	2.874E-2 +i 0.000E+0
3	1.097E+1 +i 0.000E+0	4.311E-2 +i 0.000E+0
4	1.463E+1 +i 0.000E+0	5.748E-2 +i 0.000E+0
5	1.828E+1 +i 0.000E+0	7.185E-2 +i 0.000E+0
6	2.194E+1 +i 0.000E+0	8.622E-2 +i 0.000E+0
7	2.560E+1 +i 0.000E+0	1.006E-1 +i 0.000E+0
8	2.926E+1 +i 0.000E+0	1.150E-1 +i 0.000E+0
9	3.292E+1 +i 0.000E+0	1.293E-1 +i 0.000E+0
10	3.658E+1 +i 0.000E+0	1.437E-1 +i 0.000E+0
11	4.024E+1 +i 0.000E+0	1.581E-1 +i 0.000E+0
12	4.391E+1 +i 0.000E+0	1.724E-1 +i 0.000E+0
13	4.757E+1 +i 0.000E+0	1.868E-1 +i 0.000E+0
14	5.124E+1 +i 0.000E+0	2.012E-1 +i 0.000E+0
15	5.491E+1 +i 0.000E+0	2.156E-1 +i 0.000E+0

c. **LOAD COIL DATA:** This control is used for loading the *.txt files previously created and needed for the creation of the configuration file.



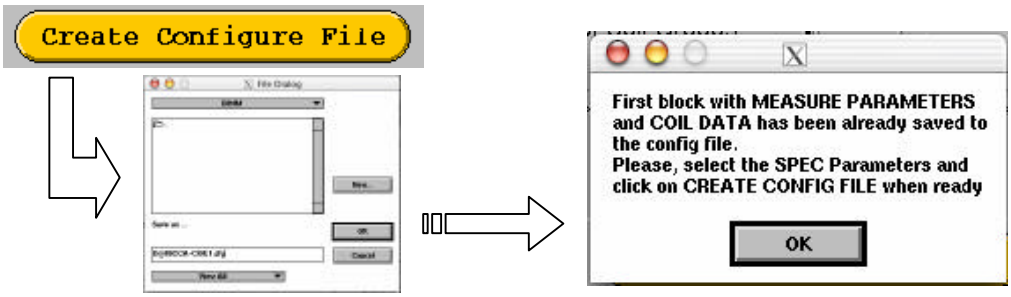
d. **LOAD COIL DESCRIPTION:** This control is used for loading the *.CCS file generated for each mole.



e. **CREATE COIL DESCRIPTION:** It is an important control because by clicking on it, the user reaches a new front panel in which the *.txt file and the *.CCS file can be created. This front panel will be described later.

5. **DATA COIL FILE:** All the above explained indicators and parameters are sourced from the *.txt file shown in this field.

6. **CREATE CONFIGURATION FILE:** When all the measurement parameters have been correctly set and an existing coil data (*.txt file) has been loaded, the first block of the configuration file will be saved if this control is clicked. If the saving process has been succesful, a confirmation message will be appears.


Create Configure File
First block with MEASURE PARAMETERS and COIL DATA has been already saved to the config file.
Please, select the SPEC Parameters and click on CREATE CONFIG FILE when ready
OK

7. **COIL SET DEFINITION:** This part is not used.
8. **MAGNETIC SETTINGS:** With these two buttons, the fields related to the magnet and the coil data file can be saved and/or loaded. The extension of this kind of files is *.RCD. This is a useful, fast way of dealing with the setting for creating configuration files.

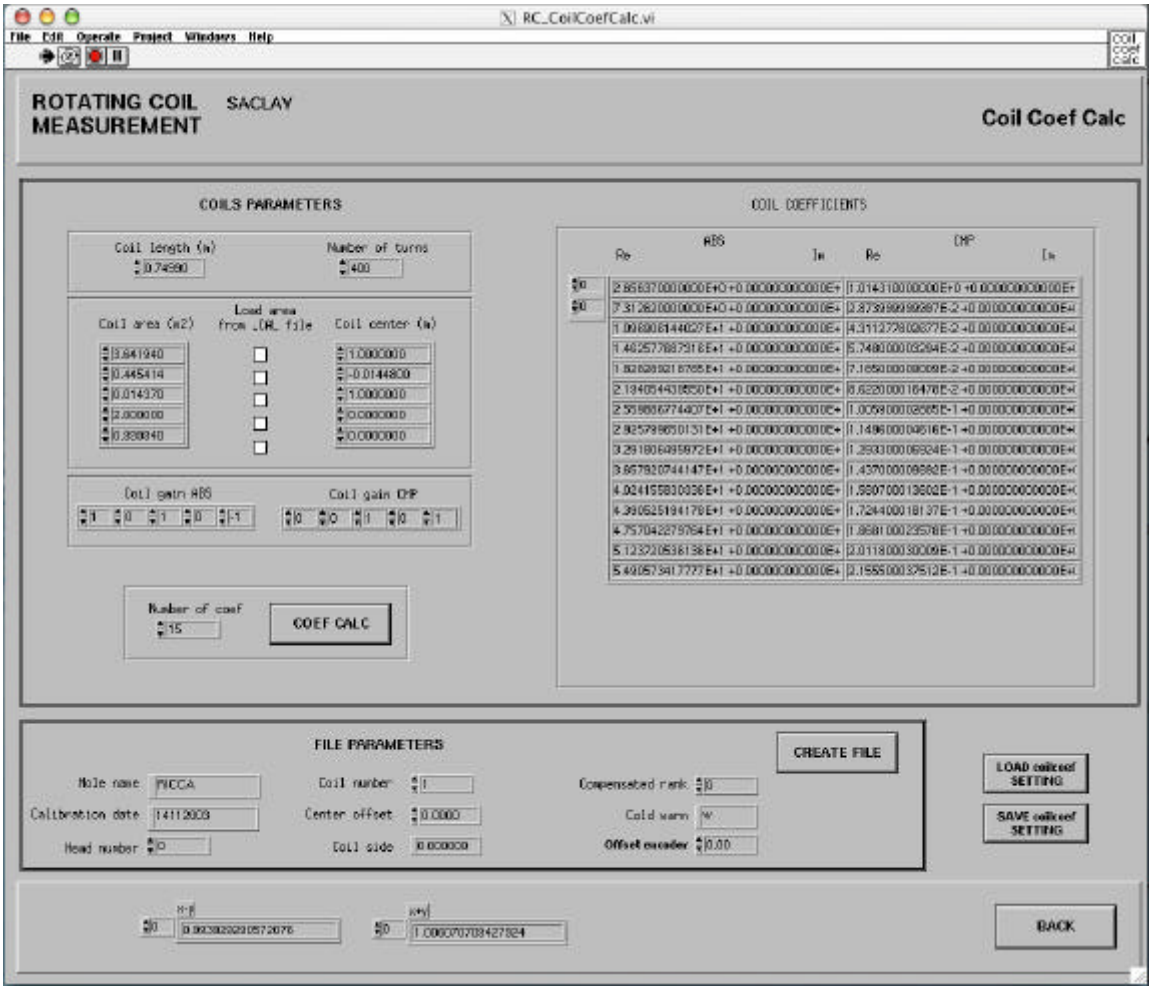
9. **SETUP OPTIONS:** With these three controls the user will be able to check the ADC card, the processor, integrators... change ADC channels, serial ports, data paths and control files...

10. **DRIVERS:** It also exists the possibility of testing the power supply and the NMR drivers from this panel. The Shaft control Panel has no sense since there is no axial movement in the calibration procedure.

11. **MEASUREMENTS:** These two controls enable the user to perform a magnetic measurement and to check if it has been successfully completed.

12. **EXIT:** By clicking on it and after confirming the decision, the execution of the program is stopped and the panel is closed.

- **CREATING COIL DESCRIPTION.**



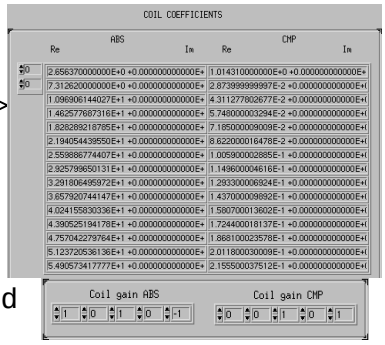
This screen is reached if this button in the previous panel is pressed.

The user must get used to work on this important screen because the *.txt and *.CCS files will be created here. Those will perfectly describe the mole and its coils inside. There would be one *.CCS file for each mole and as many *.txt files as coils inside the mole. The list of choices are now described:

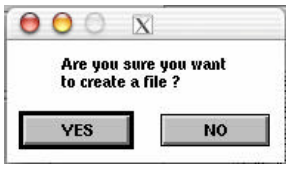
1. **FILE PARAMETERS:** These parameters give general information about the mole and coils. There are important ones that must be properly set because they will become part of most of the saved files: Mole name (the name of the

mole to be used), Coil number (the position inside the mole that the current coil occupies: i.e. if there are five coils, selecting '1' it corresponds to E1; '2' to M1; '3' to C; '4' to M2 and, finally, '5' for referring to E2), Compensated rank, Calibration date, Center offset, Cold/warm, Head number, Coil side and Offset encoder.

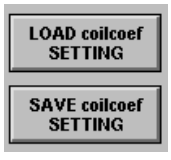
2. **COIL PARAMETERS:** These are mechanical parameters: the length of the mole, the number of wiring turns, the area of each coil inside the mole (with the possibility of loading them from a file) and the coil center position (in m).
3. **COIL COEFFICIENTS:** The generated coefficients (harmonics) depend not only on the above coil parameters but also on the gains of the measurement type (Absolute or Compensated). The number of coefficients must also be set (normally to 15) before clicking on "COEF CALC" in order to generate the results and show them on the table.



4. **CREATE FILE:** Once one is sure that all the fields are correctly filled in, it is time to create the *.txt file with this option.

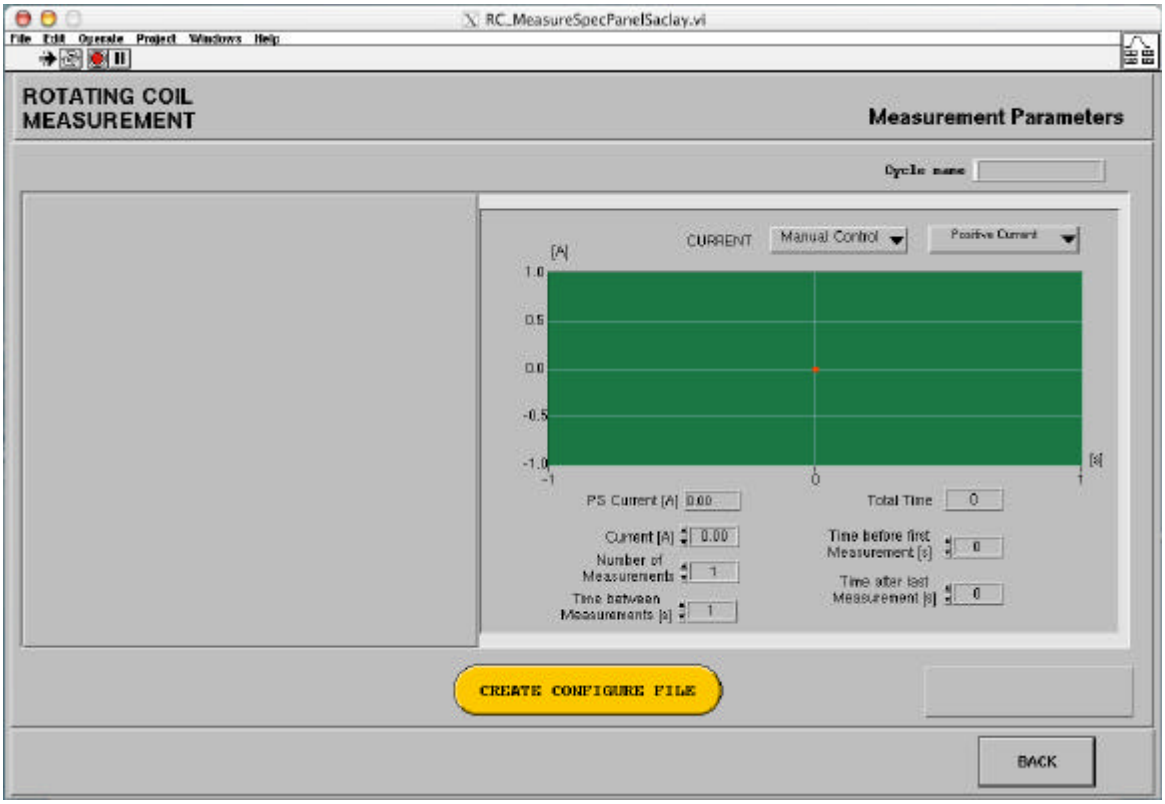


5. **COIL COEFFICIENTS SETTINGS:** With these controls, *.CCS files are loaded (same utility as the one explained on MMP 4.d) or saved.



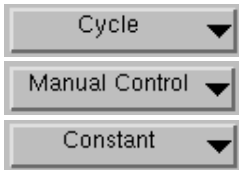
6. **BACK:** Closes the panel and returns to the previous one.

- **MEASUREMENT PARAMETERS. CONFIGURATION FILE (II).**

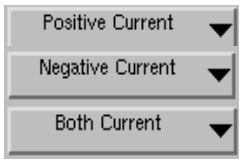


This window is the one with which the creation of the configuration file process is completed. The options available are the following ones:

1. **CURRENT MODE:** This control is used to select the mode of the current set to the power supply. One can select a cycle, a constant current (that means also REMOTELLY controlled, via GPIB) or manual control (not controlled via GPIB).

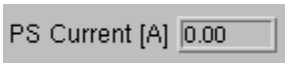


2. **CURRENT TYPE:** The different choices to be selected are positive current, negative current or both of them (the number of measurements will double, then, in this last case).

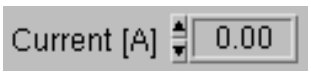


3. **CYCLE NAME:** It shows the name of the cycle selected.

4. **PS CURRENT (A):** It is displayed the value of the real current.



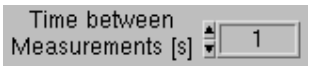
5. **CURRENT (A):** The desired or expected current that the user would like to drive to the magnet is controlled. It is **REALLY important** to set this value independently of the current mode selected.



6. **EDIT CYCLE:** This control opens a new window in which a cycle can be edited. It is only visible if cycle current is selected in current mode.

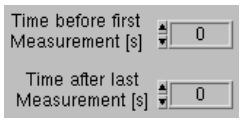
7. **NUMBER OF MEASUREMENTS:** The number of measurements to be performed can be set here.

8. **TIME BETWEEN MEASUREMENTS:** The waiting time between one measurement and the next one.

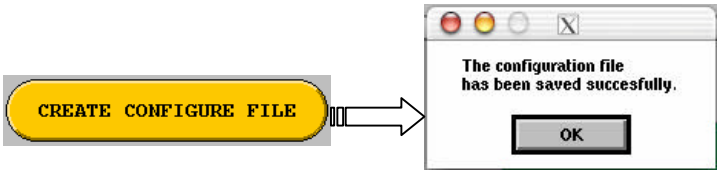


9. **TOTAL TIME:** Indicates the total time that takes the measuring process.

10. **TIME BEFORE FIRST/AFTER LAST MEASUREMENT:** Do not care about them because they will be constants.

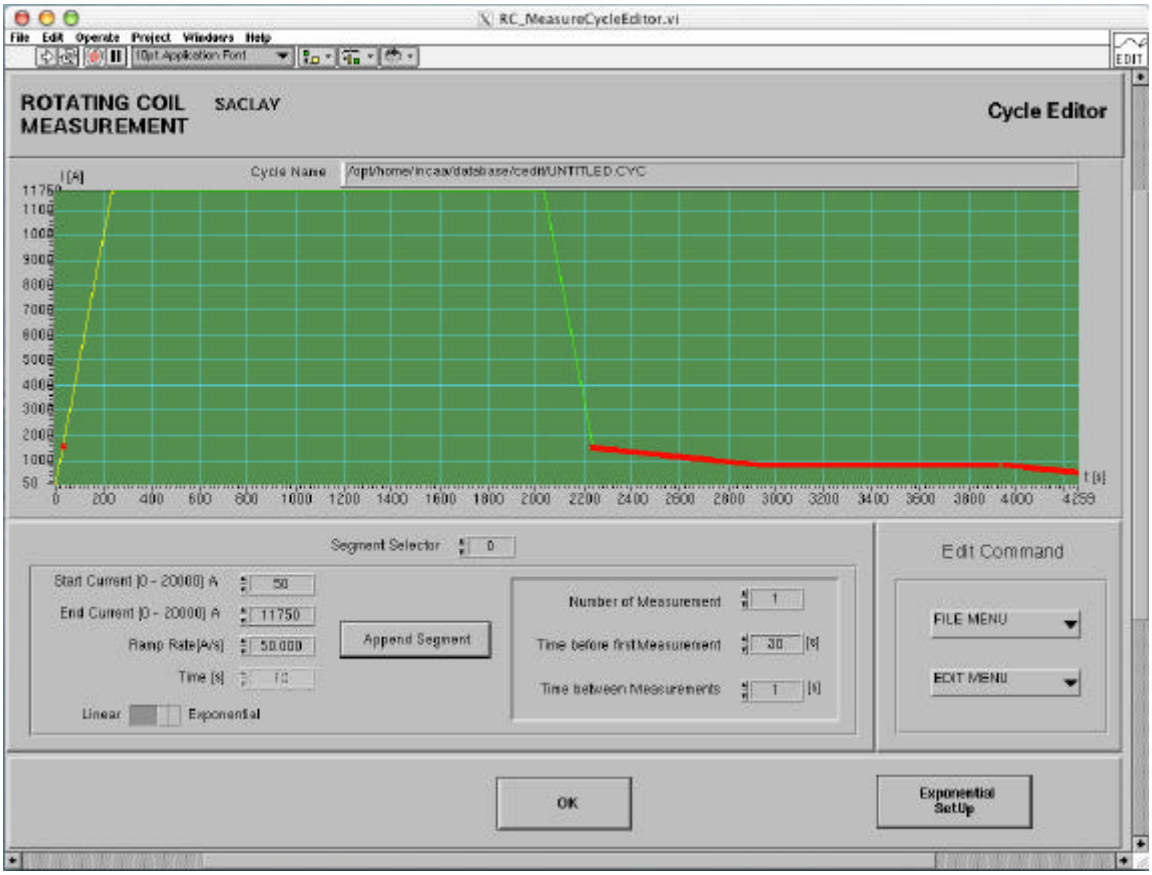


11. **CREATE CONFIGURATION FILE:** If there are no problems with the selections, the configuration file is completely saved.



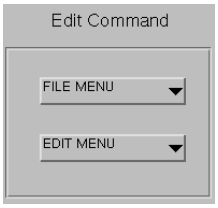
12. **BACK:** Closes the window and goes to the previous panel. If it is pressed before finishing the saving process, a warning is shown.

- **CYCLE EDITOR.**



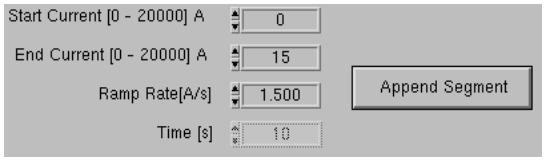
This panel allows the user to configure a personalized cycle of current to power the magnet. The current cycle can be divided in segments forming different kinds of waves (squared, triangular…) with offsets, with one or both signs… The buttons available to create them are now described:

1. **EDIT COMMAND:** There are two menus available:
   - **a.** FILE MENU: with which one can load or save a cycle.
   - **b.** EDIT MENU: with which one can delete one or all segments, insert one segment, append it or append a complete cycle.



2. **LINEAR/EXPONENTIAL:** The type of current of each segment can be switched from linear to exponential with this selector.

3. **SEGMENTS:** The segments must be edited one by one. These controls select the Start Current, the End Current and the Ramp Rate. The Time is normally expected and calculated to be 10 s but it depends on the previous parameters. If the end current of the last segment and the start current of the new one do not match, then it is not enabled. The "Append Segment" button updates the changes in the actual cycle edition.

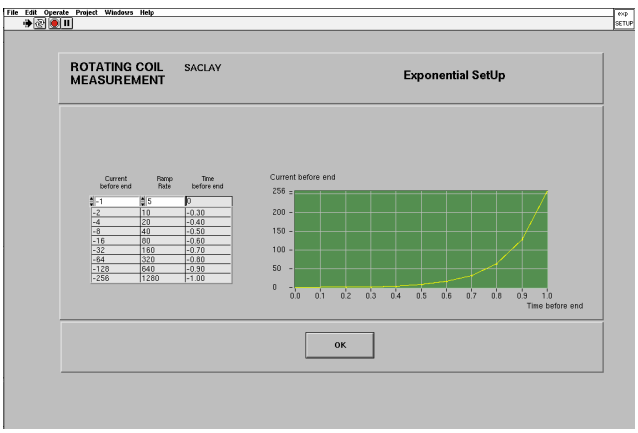


4. **SEGMENT SELECTOR:** Allows to move from one segment to another and also to check its settings.

5. **CYCLE NAME:** Shows the name of the current cycle.

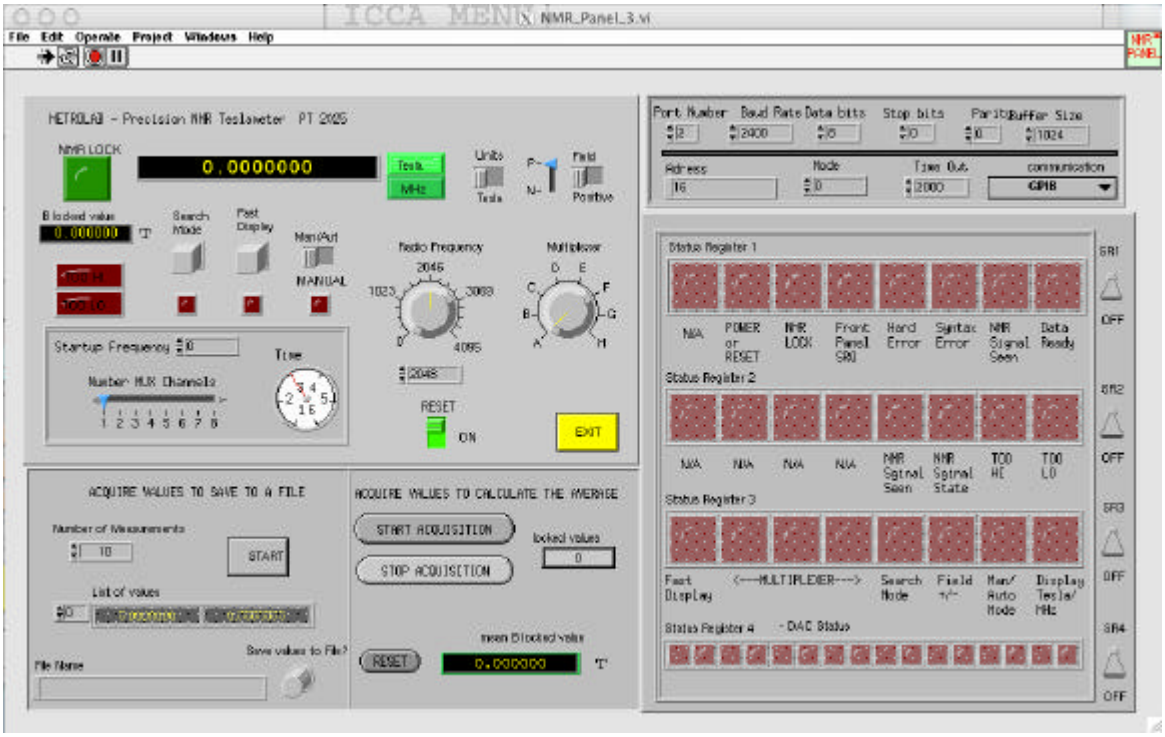
6. **GRAPHIC:** Displays the shape of the current.

7. **EXPONENTIAL SETUP:** By clicking on it, the user can set up the exponential growth of the current.



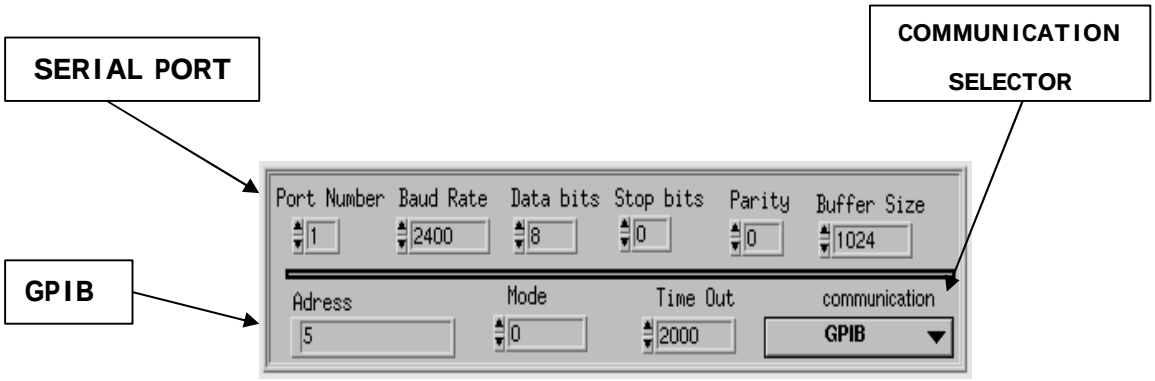
8. **OK:** Stops the execution of the VI and goes back to the previous panel.

- **NMR TESLAMETER.**



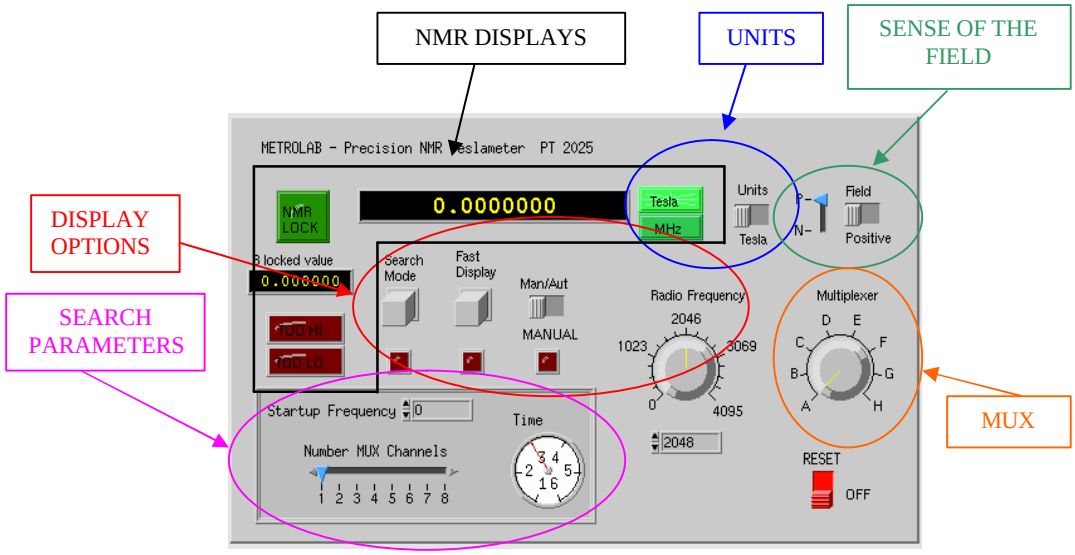
This is the front panel that remotely controls the NMR Teslameter PT 2025 so that to achieve a stable locked field value from the magnet under test. It can be called in a test mode (only to check the functionality) from the previous panels or at the time a coil area calibration wants to be done. All the options available are described below:

1. COMMUNCATION PARAMETERS:


SERIAL PORT
COMMUNICATION SELECTOR
GPIB
Port Number Baud Rate Data bits Stop bits Parity Buffer Size
1 2400 8 0 0 1024
Adress Mode Time Out communication
5 0 2000 GPIB

The communication with the instrument can be established by three different ways: RS232, GPIB and RS232-GPIB. This last one is not used in this calibration program. With the communication selector on the right-bottom corner of the control, the interface can be selected. The upper part is destined to set the serial port parameters. It is recommended not to modify the predetermined values that exist by default unless it is necessary (different port number or address…).

2. CONTROLS AND INDICATORS:



These are the main controls and indicators that let the user reach a stable locked value depending on the measuring conditions (periphery hardware available, kind of connections…):

a. **NMR DISPLAYS:** The two red ones indicate that the Teslameter is locked, but it is not at the center of the field tracking range. The small black one shows the last field locked value measured, and the large black one is the normal NMR reading. The green one is set on every time a locked value is achieved.

b. **UNITS:** With this control one can determine whether the displayed values are given in Tesla or in MHz.

c. **SENSE OF FIELD:** The sense of the field to be measured with respect to the orientation of the probe can be controlled with this switch. Note that if the field +/- is in the wrong sense, the PT 2025 does not lock on to the NMR signal!

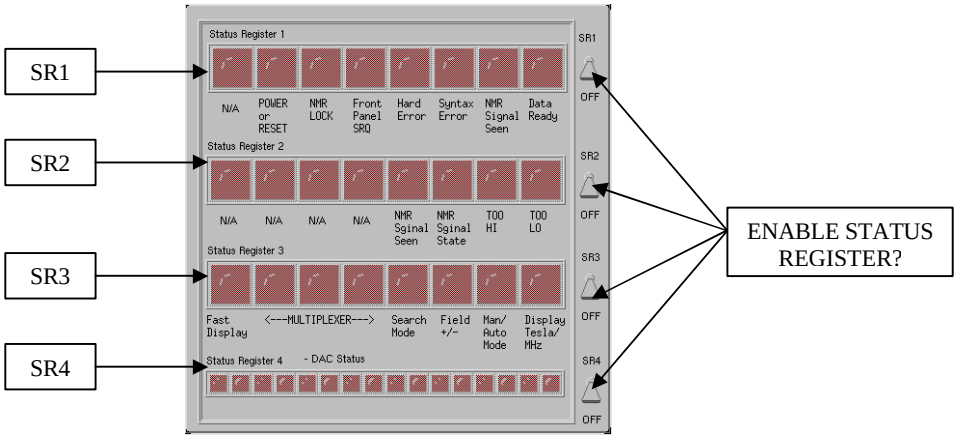
d. **DISPLAY OPTIONS:** With these controls the user: can activate the automatic field searching algorithm (Search Mode), increase the display reading rate from ~1 to ~10 (Fast Display), preselect a radio frequency sent to a 12 bit DAC (Radio Frequency) and sweep this radio frequency over the whole range of the FINE potentiometer (5% of the selected one) until the signal is locked (Auto Mode).

e. **MUX:** In case there was more than one channel to scan in Search Mode, it could be changed with this knob.

f. **SEARCH PARAMETERS:** These controls allow to change the speed of the search (Time: 1 most rapid, 6 lowest one) rapid), to set the number of channels connected using Search mode and to supply (optionally) a start frequency if the approximate field value is known.

g. **RESET:** Leads the execution of the program to an initiated, known state.

3. **STATUS REGISTERS:** PT 2025 has got 4 internal status registers that can be accessed by the user, enabling the desired one with the controls on the right, in order to check, at any time, the status of the instrument:



a. **SR1 (Internal Instrument Status).**

b. **SR2 (NMR Signal status).**

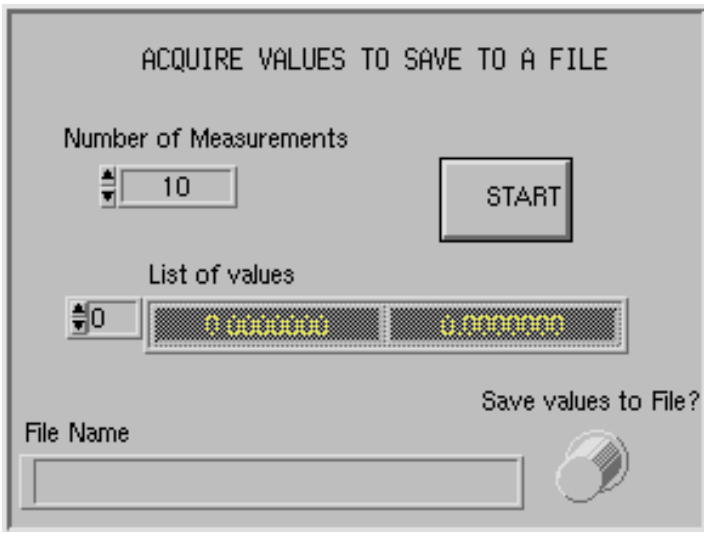
c. **SR3 (Instrument Functions).**

d. **SR4 (DAC Status).**

Note that while enabling the four status registers at the same time, it may cause a decrease of the flux information's speed!!

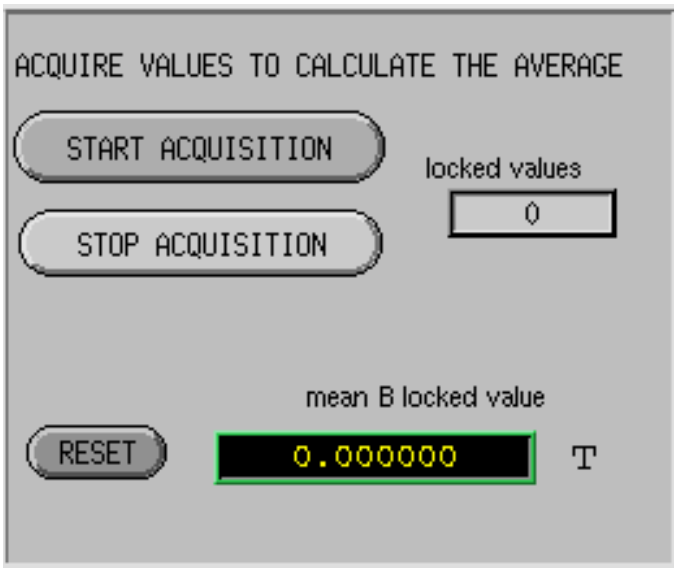
For further information about the contents of the status registers, please, refer to the "*NMR TESLAMETER HIGH PRECISION PT 2025 BENCH UNIT MANUAL" METROLAB Instruments SA*.

4. ACQUIRE VALUES TO SAVE TO A FILE:



Some other options are available: A number of lectures (normal NMR reading values), selected by the user, can be saved in an array (after pressing the "START" button). Afterwards, if it is desired, these values can be saved to a file (must be specified its path and name) by clicking on the "Save values to File?" button.

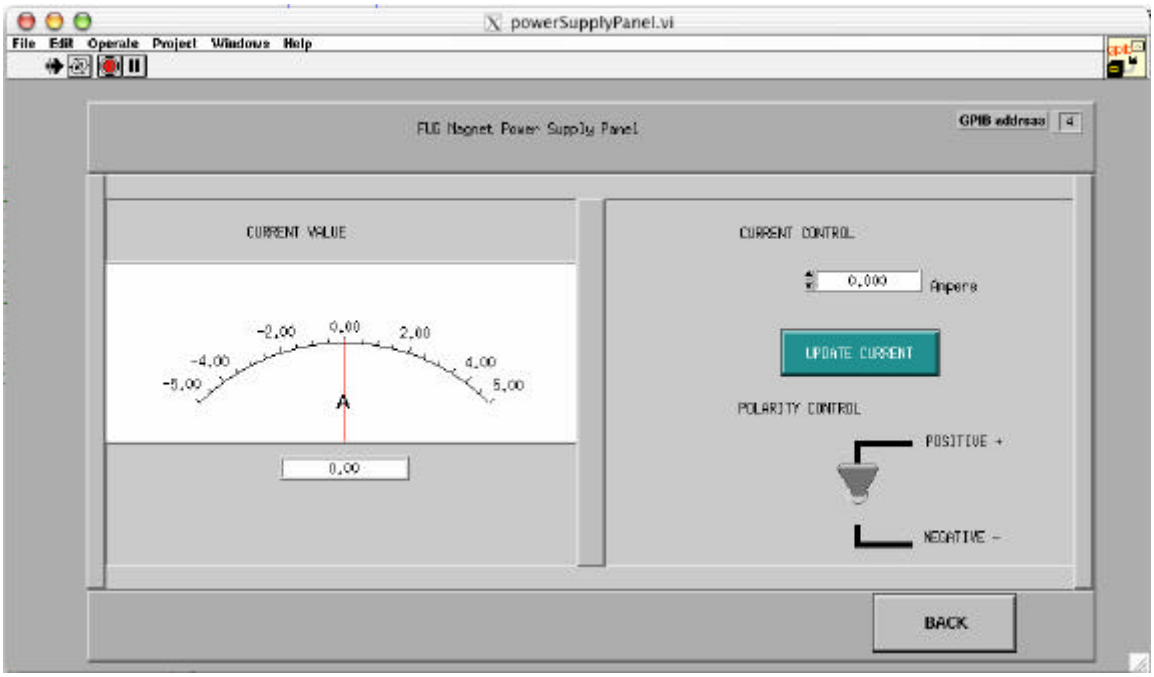
5. ACQUIRE VALUES TO CALCULATE THE AVERAGE:



These options allow the user to store an undefined number of locked magnetic field values, once the reading of the magnetoscope is stable, thanks to the buttons START and STOP ACQUISITION. The average of them will be displayed on the corresponding indicator as well as the number of lectrures acquired. The RESET button allows starting again the acquisition.

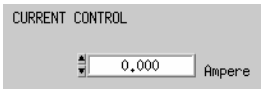
6. **EXIT:** Clicking on “Exit”, the control of the instrument is stopped and the window is closed.

- **POWER SUPPLY.**



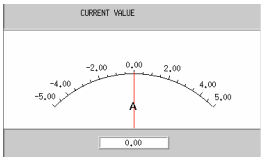
This is the panel that remotely controls the FUG Power Supply that will source current to the magnet. It is important to note and check that the power supply MUST be in remote mode!! Its simple handling is composed by:

1. **CURRENT CONTROL:** The current value desired by the user must be entered with this digital control.

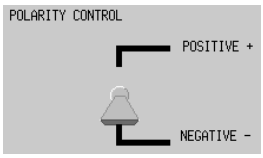


2. **UPDATE CURRENT CONTROL:** Each time a current value is selected, it must be validated so that it takes effect.

3. **CURRENT DISPLAY:** The value of the current sourced by the power supply can be read in this meter control.



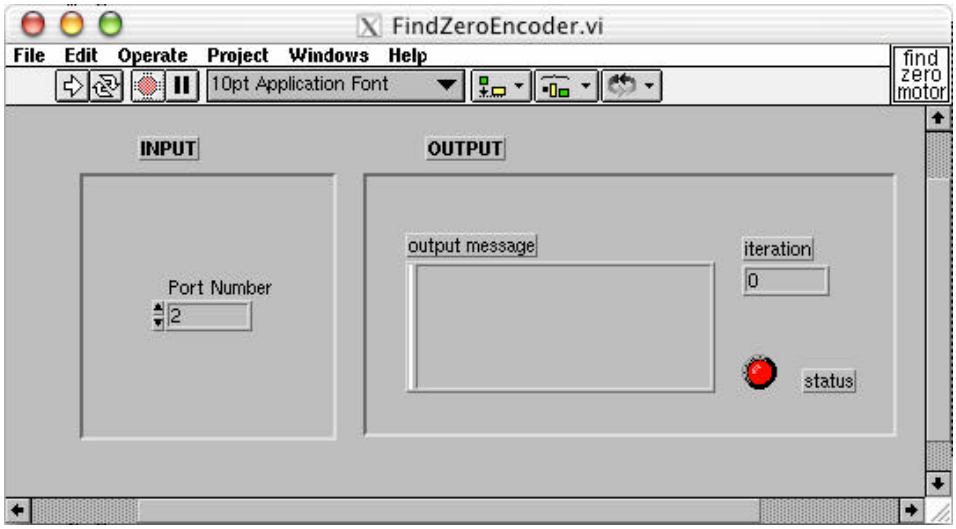
4. **POLARITY CONTROL:** The polarity of the power supply can be changed with this selector.



5. **GPIB ADDRESS:** This is the field where the GPIB address

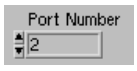
can be set.
6. **BACK:** Closes the actual front panel and returns to the previous one.

- **FIND ZERO ENCODER.**



This small window appears at the beginning of the measurement process only for a few seconds. Its function is to take the rotating motor to a known position. What we find in the front panel is:

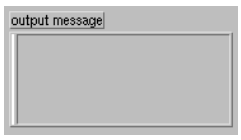
1. **INPUT:** The port number where the rotating motor is connected.



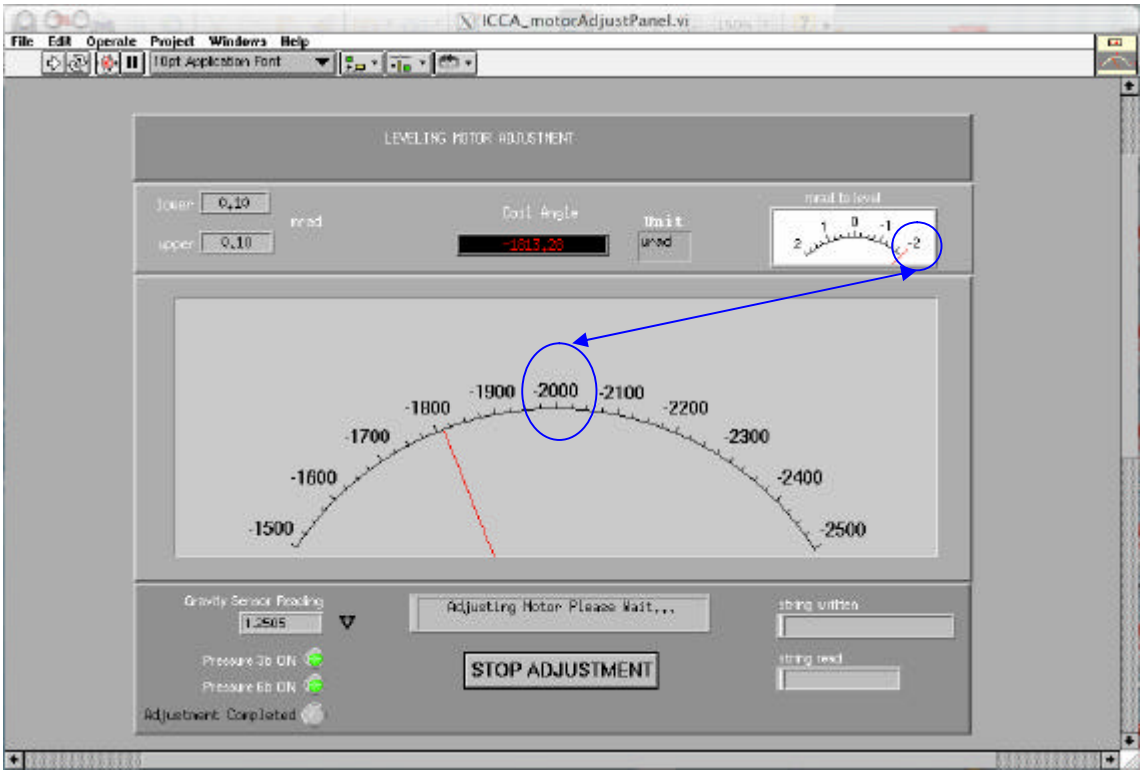
2. **OUTPUT:**
   a. **STATUS:** LED that indicates if the appropriate position has been reached.

   b. **ITERATION:** Indicates the number of iterations in course to achieve the correct position.

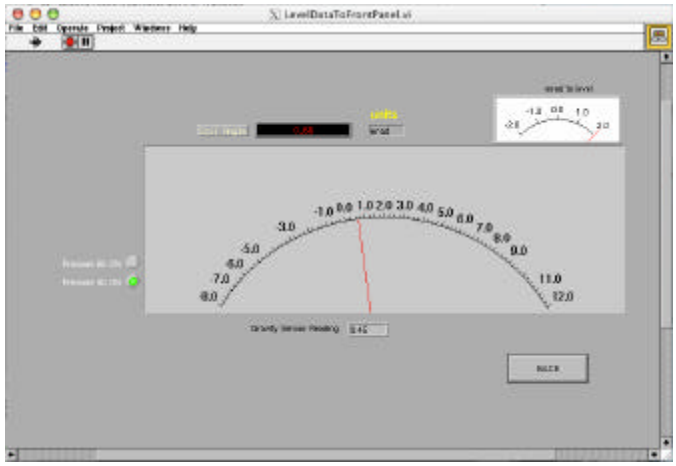
   c. **OUTPUT MESSAGE:** Indicator that shows a message confirming that the process has succeeded or warning it if has failed.



- **LEVELLING MOTOR ADJUSTEMENT.**



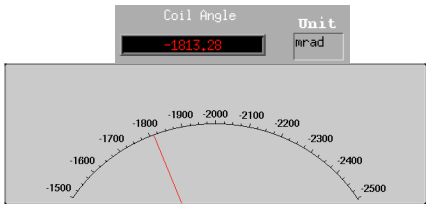
In this screen it can be seen how the leveling process takes place immediately after the rotating motor reaches the correct position for starting the measurement, in an automatic way. This panel is only shown if: a QIMM system is being used or, in case of using DIMM, the goal is 0 mrad. In other cases, the panel that appears is this one (for leveling the mole manually):



The controls and indicators offered to the user are:

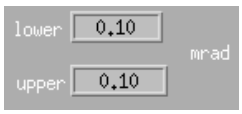
1. **mrad TO LEVEL:** Indicates the value to which the user wants to level the mole.

2. **COIL ANGLE:** Displays the angle of the mole in every moment. While the needle approaches the goal, the coil angle value is updated in both indicators: analogical meter and digital. When the difference between the real value and the one it is desired to achieve is less than 1 mrad and also less than 0.5 mrad, the range in the meter indicator (the maximum and minimum value shown) is properly fitted and the units in the digital one are changed to μrad.

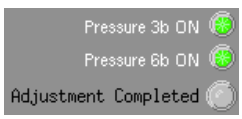


3. **GRAVITY SENSOR READING:** This is the value of the tilt sensor after reading the ADC card and converting it into Volts. The relationship between this value and the coil angle is: 1 V → 1.45 mrad.

4. **LIMITS:** These two indicators show the range in which the leveling process should be stopped. It is expected that 10 seconds after the needle gets into these limits, the adjustment finishes.



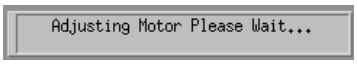
5. **LED INDICATORS:** The two first LED point if the brakes (the 3 bars and/or the 6 bars one) are set or not. The last one indicates if the coil angle has reached the limit range and, therefore, if the adjustment is completed.



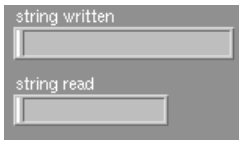
6. **STOP ADJUSTMENT:** Control with which the leveling process can be stopped. Note that the value of the coil

angle and of the gravity sensor to use in following operations will be the ones shown in the displays before exiting or clicking on it.

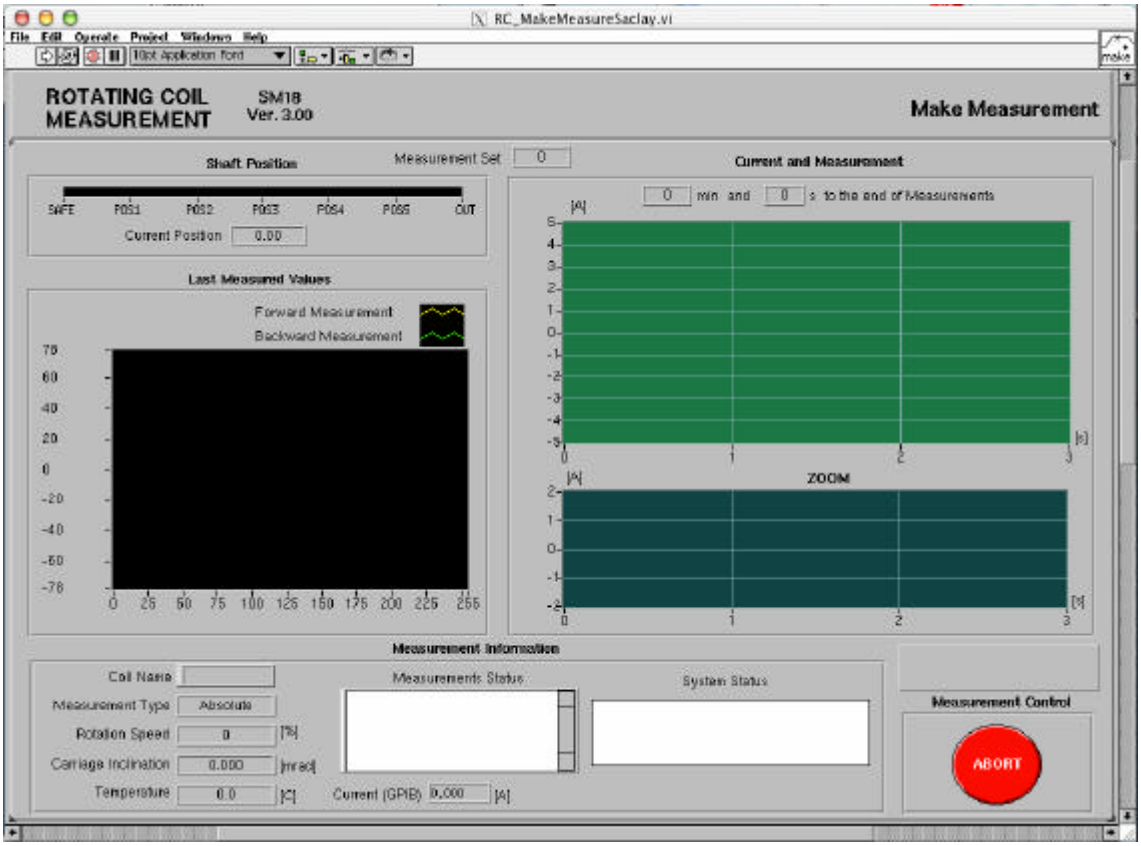
7. **STATUS MESSAGE:** Depending on the state of the adjustment, the possible messages to read are: "Adjusting Motor Please Wait…" if the process goes on with no problems, "Level within limits" if the value desired is already between limits (before starting the leveling process), "Adjustment completed" if the corresponding LED is on and "Adjustment stopped" if the adjustment has been forced to stop.



8. **STRINGS:** Shows the commands sent to the rotating motor via serial port and the answers received.

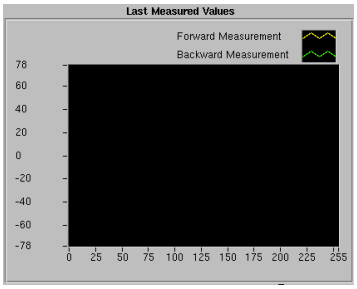


- **MAKING MEASUREMENTS.**



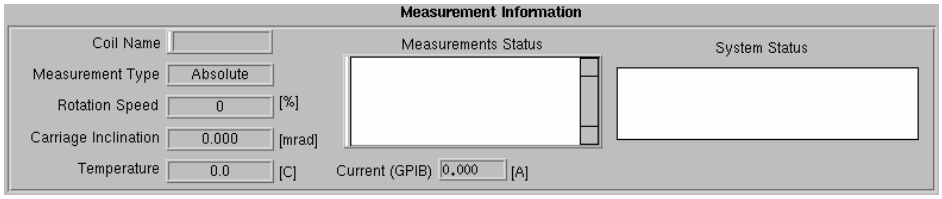
Once the mole has been leveled, the measurements start. This screen allows the user to constantly check the evolution of them and their characteristics. This is the list of information one can find here:

1. **SHAFT POSITION:** This information is no longer useful since there is no axial movement on the shaft.
2. **LAST MEASURED VALUES:** This graphic shows the results of each measurement. The yellow curve corresponds to the magnetic flux achieved from the forward measurement and the green one, from the backward measurement. In the



horizontal axis, 256 points corresponding to 256 acquired values per turn are shown as well as the value of the flux in the vertical axis.

3. **MEASUREMENT INFORMATION:** In these fields there is general information about the measurement and its state. This is:



   a. **COIL NAME:** The name of the mole that is being measured.
   b. **MEASUREMENT TYPE:** The type of measurement selected at the moment of the configuration of the file.
   c. **ROTATION SPEED:** The speed of the rotation of the mole in %.
   d. **CARRIAGE INCLINATION:** The value of the Tilt Sensor reading at the time the measurement takes place.
   e. **TEMPERATURE:** The temperature at which the measurement is made.
   f. **CURRENT (GPIB):** The current read via GIB from the power supply (or the Specified one if manual current is selected).
   g. **MEASUREMENT STATUS:** The files generated from the measurements are available in this list. Their names give an idea of the status of the measurement.
   h. **SYSTEM STATUS:** Messages explaining the status of the measurement are shown here. They can be:
      i. Initializing Power Supply.
      ii. Ramping to the starting current.
      iii. Executing cycle…
      iv. Measurements are too fast.
      v. Waiting…
      vi. Measuring…

vii. Waiting x seconds for next measurement.

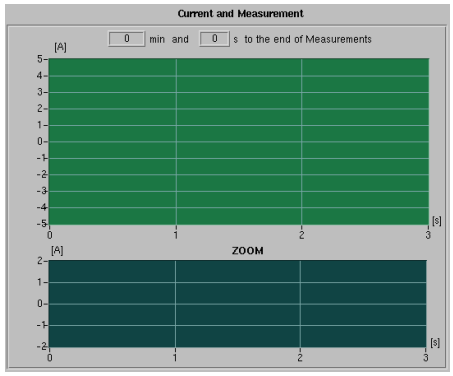
viii. Average Angle error!!! Restarting measurements.

ix. Tilt Sensor error!!! Restarting measurements.

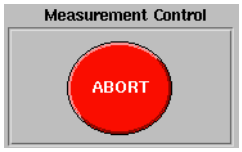
x. After 3 tries of measurements, the accuracy achieved is not acceptable. Check the brakes of the mole or try to reduce the restrictions.

xi. Exiting measurement.

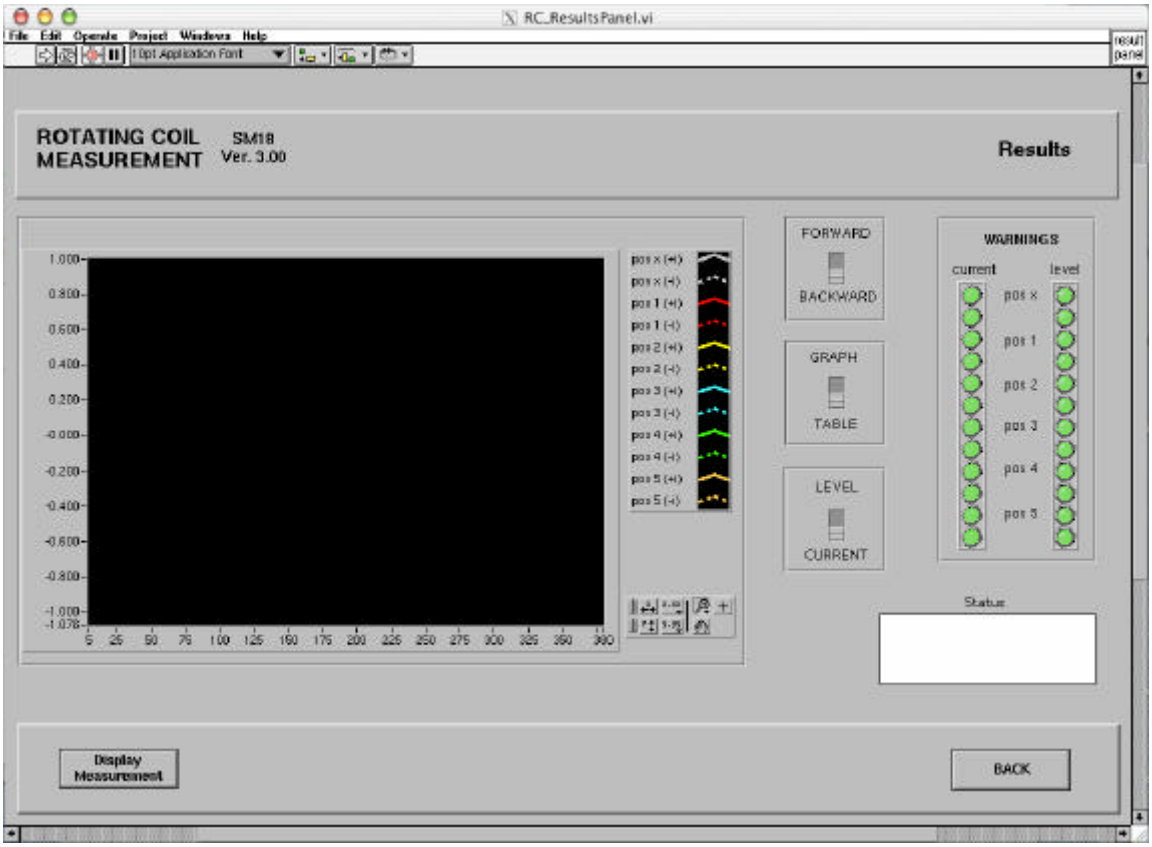
4. **CURRENT AND MEASUREMENTS:** At the beginning of the measurement, the current to be set to the Power Supply is shown in these two graphics. It is really useful when a cycle of current is intended to use. There are also two numerical indicators that show the time that takes to finish the measurements.



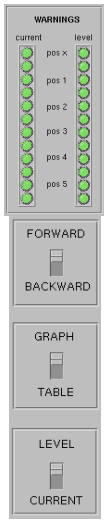
5. **MEASUREMENT CONTROL:** With this control, the process can be aborted. It is useful when any problem appears at the time of measuring and it lasts too long.



- **RESULTS.**



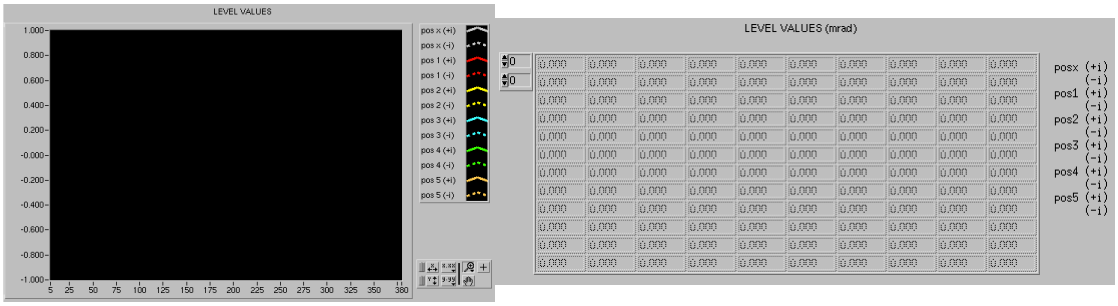
After the measurements, it is time to check the results. In this panel the user can find a general view of how the measurement has been developed: checking the current and the level values during the measurement. One can find in the front panel:



1. **WARNINGS:** There are two lists of LED that warns if some values of level or current are not between limits. The position must not be taken into account since there is no axial movement.
2. **CONTROLS:** There are three switches with which different kind of information can be displayed in the graph or in the table:

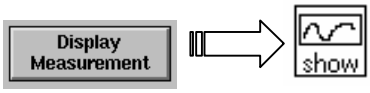
    a. **FORWARD/BACKWARD:** To display information related to the forward measurement or to the backward one.

b. GRAPH/TABLE: The information is displayed in a graph or in a table, depending on what is selected.



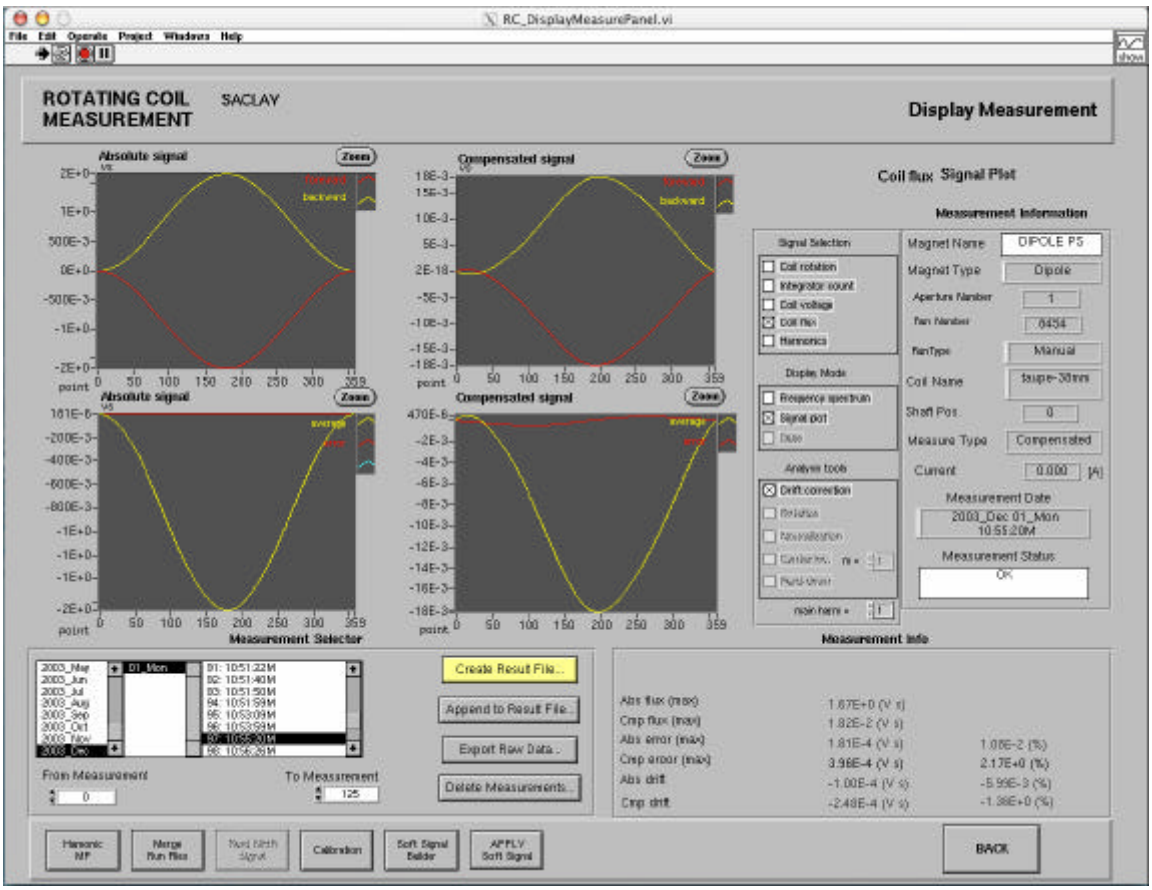
c. LEVEL/CURRENT: To display values referred to the levelling or to the current set during the measurement.

3. **STATUS:** It is not used anymore.
4. **DISPLAY MEASUREMENT:** This control allows the user to open a new panel in which a more detailed view of the results of the measurements and a complete analysis is available.

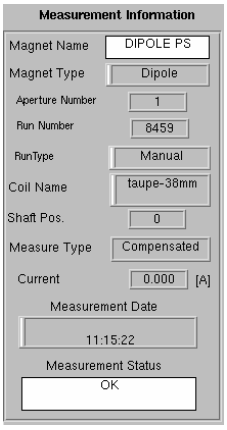


5. **BACK:** This front panel is closed.

- **DISPLAY MEASUREMENT.**



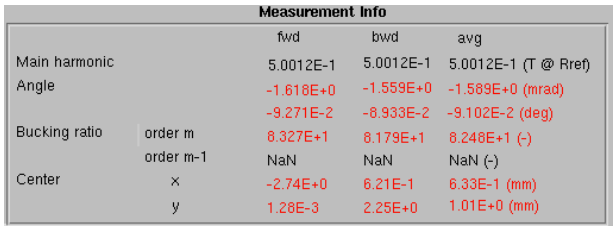
All kinds of necessary analysis can be found in this panel to analyze and to check the quality of the magnetic field. Files with the results generated by the different measurements are stored separated by year, month, day and hour of creation. That way, they can be loaded and easily identified in every moment. All the controls, indicators, graphics… are described below:



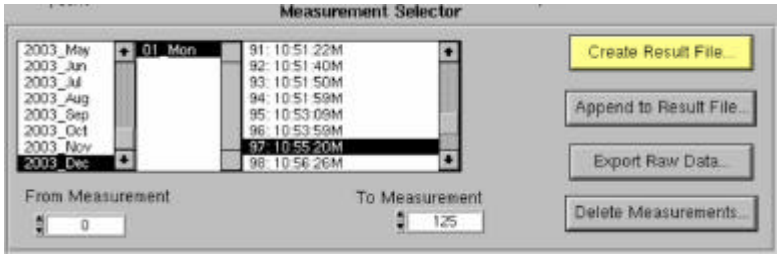
1. **MEASUREMENT INFORMATION:** In these fields it is shown important information such as: the magnet name (to know with which one is related the graphics shown), the magnet type (Dipole, quadrupole, sextupole…), the aperture number (it does not care since there is only one aperture),

the run number (number of times a measurement has been made), the run type (not used), the coil name (name of the whole mole), the shaft position (does not care), the measurement type (Absolute or compensated), the current (the current at the end of the measurement), the measurement date (only the hour is displayed there) and the measurement status (indicates the source of error if proceeds).

2. **MEASUREMENT INFO:** This part of the panel shows numerical information related to the graphics displayed. The information displayed changes as the kind of signal does. That way it is shown here in a summarized way, all the important information generated in the measurement.

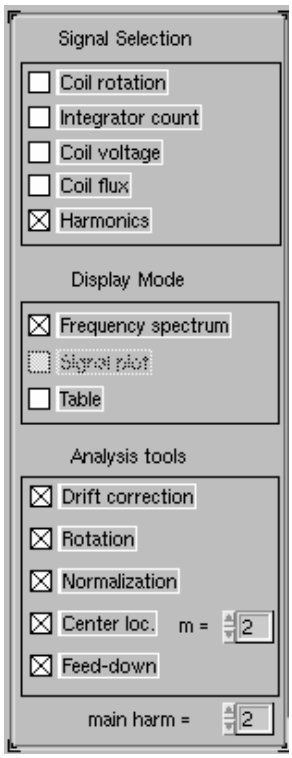


3. **MEASUREMENT SELECTOR:** These lists and controls allow the user to select the files that have been generated in previous measurements. They are ordered by year, month, day of the week and hour. It can be selected one file (to see the results saved) or some of them (to delete them, for instance) with the two controls "From Measurement" "To measurement". Also, with the controls on the right, one can create a new result file, delete an existing one and export raw data.

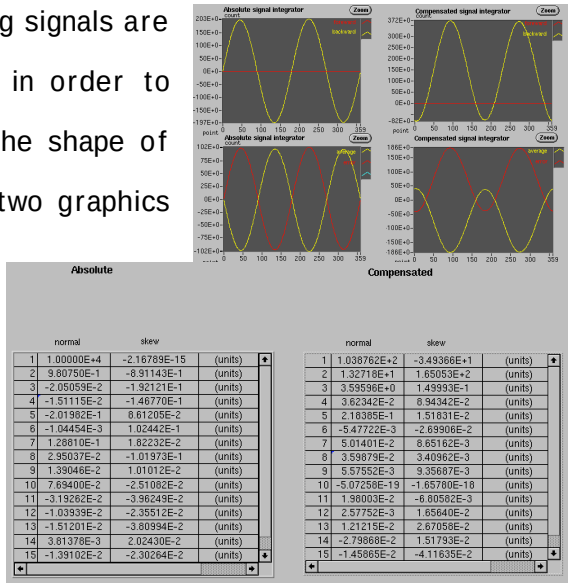


4. **MEASUREMENT CONTROLS:** There are three different kinds of selectors.
   - **SIGNAL SELECTION:** Only one choice can be selected at a time. These are the differrent graphics it can be shown from the measurement: Coil rotation (speed, time and degrees), Integrator count (signal reconstructed from the integrator in counts), Coil Voltage (signal

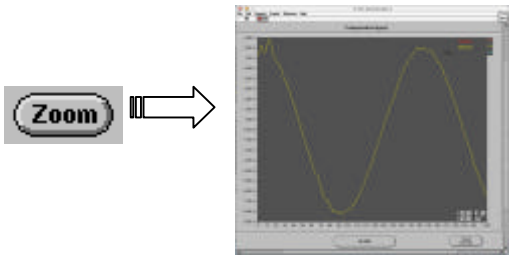
reconstructed from the lecture in Volts), Coil flux (graphic of the flux of the signal) and Harmonics (normally the representation of the first fifteen harmonics).



- **DISPLAY MODE:** It can be chosen the way the kind of signal selected is going to be shown, as well. That means: Frequency spectrum (the spectrum in frequency of the selected signal will be displayed), Signal plot (the standard graphical representation y/x) or Table (the values are displayed in a table instead of in a graphic).
- **ANALYSYS TOOLS:** These are multiple selectors that can add new parameters in order to modify the analysis results: Drift correction, Rotation, Normalization, Center location And Feed-down. “m” is the order and the main harmonic that depends on the magnet type.
- **GRAPHICS/TABLE:** Resulting signals are displayed in the 4 graphics in order to facilitate a visual test of the shape of them. They are divided in two graphics for absolute measurements and two more for compensated ones. As the “Measurement Info” part does, the graphics change their shape depending on the type of signal selected. For some of the choices selected, a table is



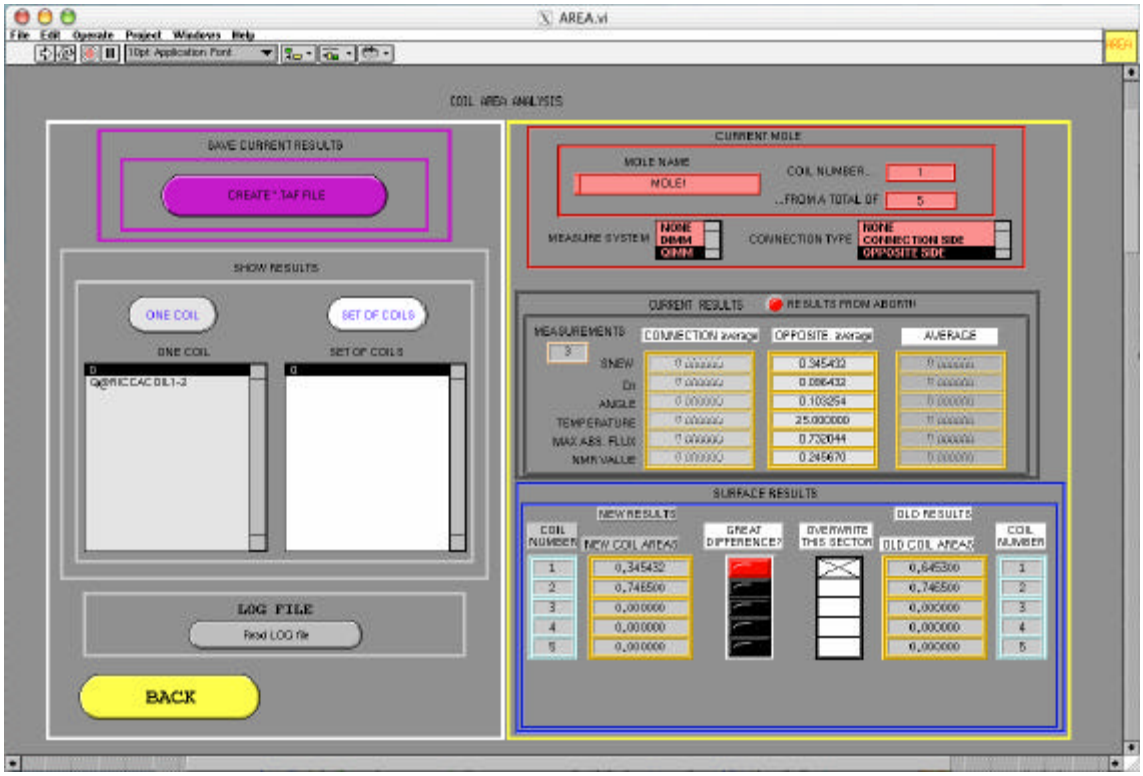
available so that the exact values could also be checked. For the graphics, there is a zoom option with which one of the graphics can be zoomed in order to see details in one part of the signals. There, the scale factors can be also modified in case harmonics want to be compared.



5. **OTHER POSSIBILITIES:** It exists some other choices that maybe are not very useful for the main purpose of the project: One can analyze the harmonics of a simple or a merged run file, merge some of the existing run files, read the value of the field and save the surface and the angle of the coil, make a quick calibration measurement or build a software signal.

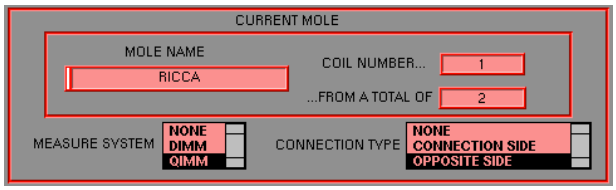
6. **BACK**: Passes the flux of the program to the previous front panel.

- **COIL AREA ANALYSIS**



This panel is displayed once the measurement has been finished and after having selected a coil area analysis option in the main menu. The purpose of this panel is to compare the new values of the coil areas with the old ones. If the difference between them is great enough, those old values can be overwritten. To manage all this procedure, the list of options at disposal of the user is:

1. **CURRENT MOLE:** Gives information about the mole it has been measured, about the file that will be created after the analysis of data and about some characteristics about how the measurement has carried out:



a. **MOLE NAME:** The name of the mole that was used for the measurement.

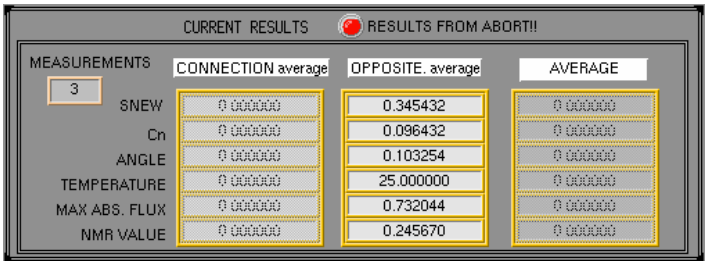
b. **COIL NUMBER:** To identify which coil inside the mole was selected. If it is zero, then it means that a file from a "set of coils" list has been loaded (and, hence, all of the coils are selected, not only one).

c. **…FROM A TOTAL OF:** The total number of coils that composes the mole.

d. **MEASURE SYSTEM:** Shows which system was, or should have been, used for the measurement with the current mole.

e. **CONNECTION SIDE:** Indicates how was the connection of the mole during the current measurement.

2. **CURRENT RESULTS:** The results extracted from the last measurement or from a loaded file are shown in these lists. Depending on the connection, they appear in one or the other list of values (CONNECTION or OPPOSSITE average). If the complementary results were already saved (for instance, an opposite side set of measurements has been finished and a connection side one had already been saved related to the same file), the three lists are shown since it is supposed that there is enough information to achieve a reliable new coil surface value:



a. **RESULTS' LED:** This LED indicates if the values below are extracted from successful measurements

or on the other hand, from aborted ones. In this last case, the results should not be taken into account and not be saved in files since it is supposed they are not correct.

b. **MEASUREMENTS:** Field that shows the number of measurements that have been made.

c. **CONNECTION/OPPOSITE average RESULTS:** The average of all the results extracted in the different number of measurements is displayed there, depending on the kind of connection. It is needed measurements in both sides (Connection and Opposite side) of the same mole so that to achieve reliable results.

d. **AVERAGE RESULTS:** The average of the results from both previous lists is shown in this array. The results to be shown are:

   i. **SNEW:** The new value of the surface in m.

   ii. **Cn:** The value of the main harmonic.

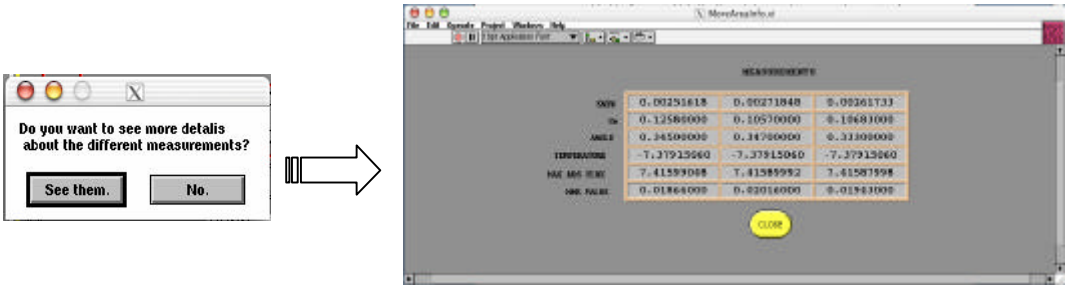
   iii. **ANGLE:** The value of the field angle in mrad.

   iv. **TEMPERATURE:** The value of the temperature during the measurement.

   v. **MAX. ABS. FLUX:** The maximum value of the absolute magnetic flux.

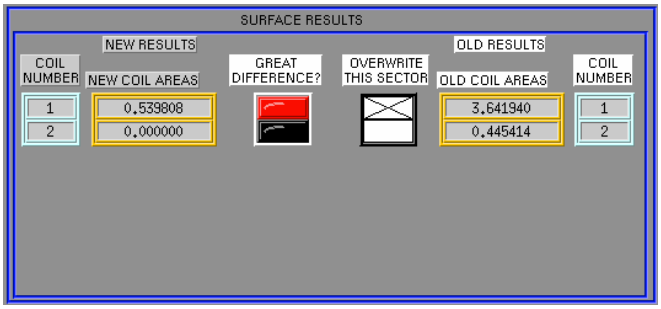
   vi. **NMR VALUE:** The value read from the NMR in Teslas.

If the results shown have been generated by more than one measurement, then a message appears, moreover, offering the possibility of checking the partial results obtained in each measurement.



3. **SURFACE RESULTS:** Once a new surface has been calculated, the calibration analysis must be done. There would appear as many rows in the

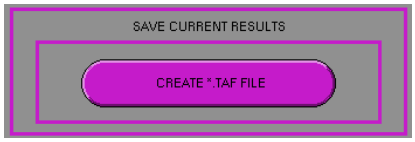
different arrays as the total number of coils into the mole indicated. The arrays on the left are referred to the new results acquired and the right one to the values that already were saved. The description of them:



a. **COIL NUMBER:** Indicates to which coil inside the mole corresponds the information in that row.
b. **NEW COIL AREAS:** Values of the new areas of the coils.
c. **OLD COIL AREAS:** Values of the old areas of the coils.
d. **GREAT DIFFERENCE?:** Array of LED that is set to red if the difference between any of the old and the new coil's area is too great. If one of them needs to be overwritten, a message like that one should be displayed:

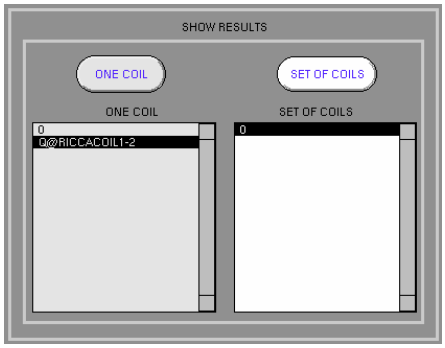
e. **OVERWRITE THIS SECTOR:** Array of flat controls with which one can select the areas that should be overwritten.

4. **SAVE CURRENT RESULTS:** Control visible only when new results, not loaded from the existing files on the lists, are displayed. This button allows the user to create a temporary area file (*.TAF) where the results will be saved. That way, results from different measurements or moles can be easily recovered.

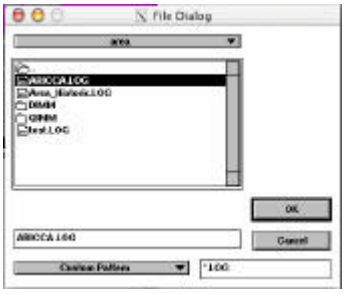


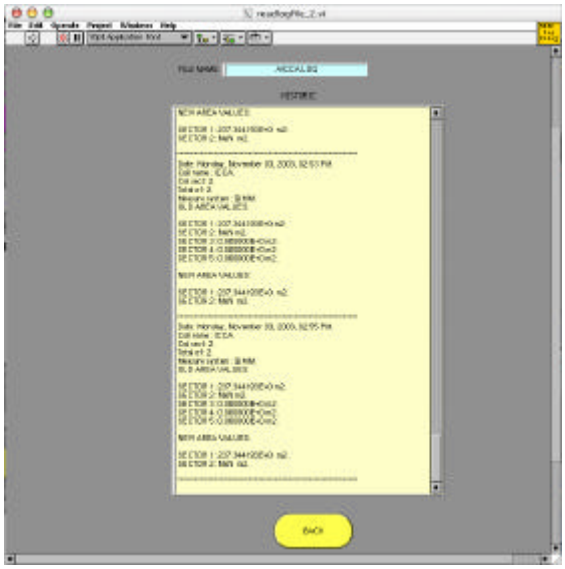
5. **SHOW RESULTS:** These controls are used for recovering results saved previously. By the time those results are saved, the lists get updated with

new files. Selecting a file from the "One coil" list, only results from this concrete coil are shown. On the other hand, if it has been chosen one from the "Set of coils" list, results from all the coils inside the mole will be visible. Anyway, once a file is selected and confirmed (with the two controls on the top), all the indicators related to this measurement (mole name, measurement system…) change.



6. **READ LOG FILE:** One clicks on this control if is interested on taking a look at the area's *.LOG file related to the mole in course in order to check which have been the lasts modifications done or just to verify if the last one already done has really been saved. As it can be seen, a new window is opened. The lists of movements are saved in it. (Note that all the LOG files name refered to the areas begin with an 'A'):



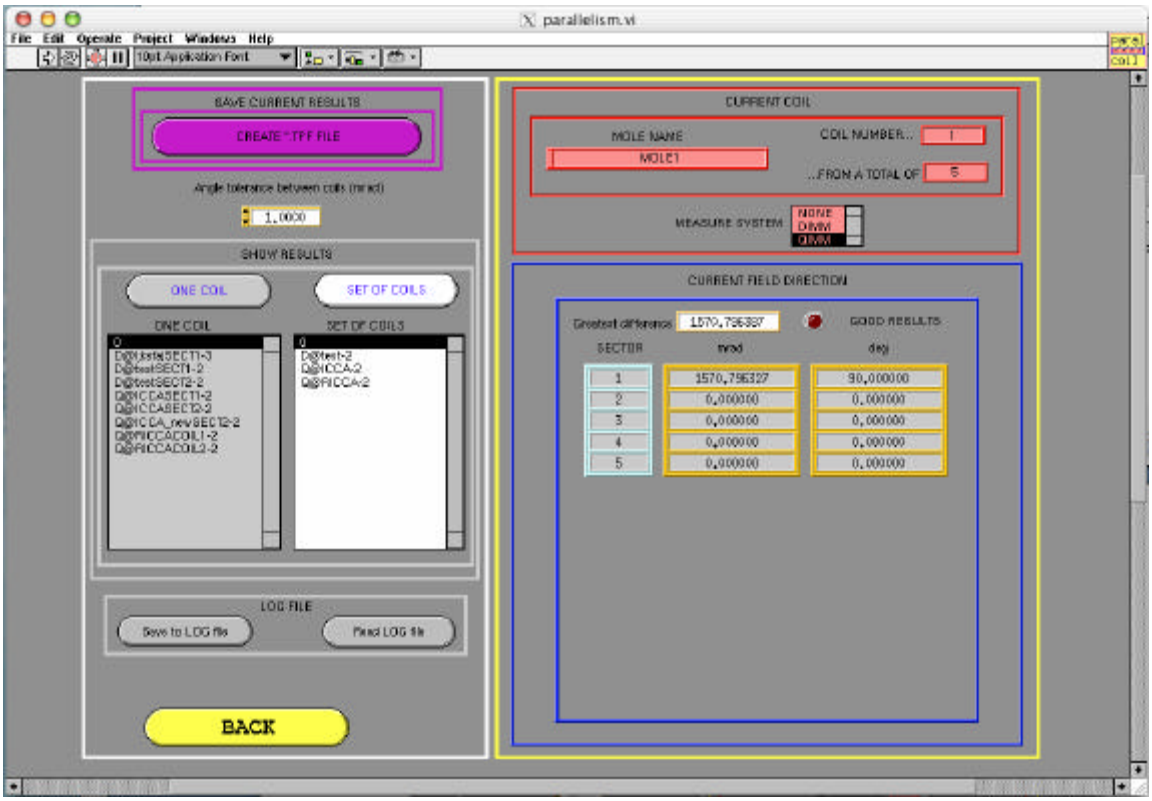


7. **OVERWRITE:** The "overwrite" button is only visible when at least one of the LED in the array is red. So, this is used to confirm the selection in the control array "overwrite

this section". Clicking on it means that the suitable files will be changed (in *.CCS and *.txt files, the old area values). As it is an important decision, one more confirmation is needed to do this. Before overwriting them, the old area values are automatically saved in the corresponding *.LOG file.

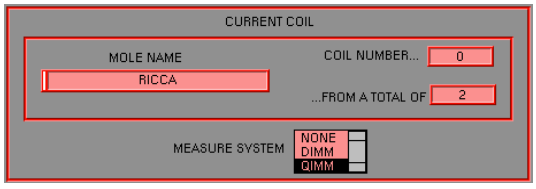
8. **BACK:** As usual, this button closes the VI in course and the flux of the program returns to the previous panel.

- **COIL PARALLELISM MEASUREMENT**



After the measurements are over, the flux of the program can pass to this panel if a coil parallelism analysis was selected. The objective of it is to check if the angle of the field in each coil inside the mole does not differ too much from the others. If the difference between them is great enough, a warning message is shown. Here they are the options available for analyzing the parallelism between the coils:

1. **CURRENT MOLE:** Remaining the same structure in all the analysis panels, these fields intend to provide information about the mole selected. Also, and although there is no need to have results from different connections as earlier, the measurement system used can also be seen:



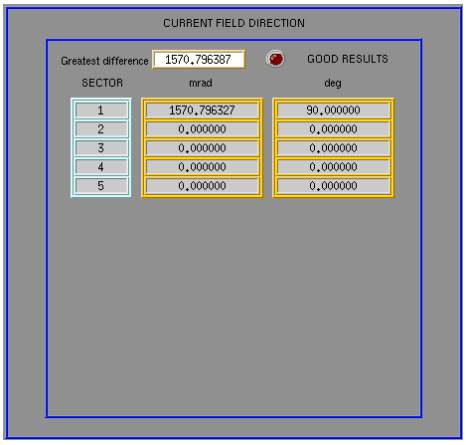
a. **MOIL NAME:** The name of the mole that was used for the measurement.

b. **COIL NUMBER:** To identify which coil inside the mole is selected. If it is zero, then it means that a file from a "set of coils" list has been loaded (and, hence, all of the coils are selected, not only one).

c. **…FROM A TOTAL OF:** The total number of coils that composes the mole.

d. **MEASURE SYSTEM:** Shows which system was, or should have been, used for the measurement with the current mole.

2. **FIELD DIRECTION:** This part indicates the angle of the magnetic field of each coil inside the mole. It is composed by:



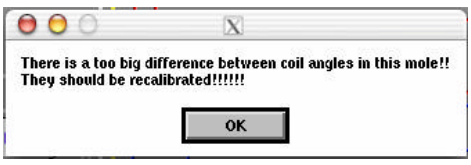
a. **RESULTS' LED:** Indicates if the results are extracted from successful measurements or from aborted ones.

b. **SECTOR:** Array that indicates the number of coil to which the results, in the corresponding row, is referred. It is displayed as many rows as the total number of coils that composes the mole.

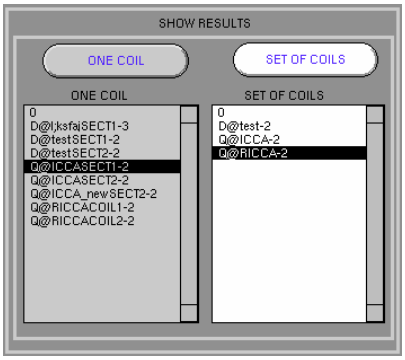
c. **mrad:** This array indicates the field value of the coils in mrad.

d. **Deg:** This one also indicates the field value but in degrees.

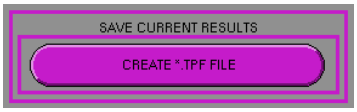
e. **GREATEST DIFFERENCE:** Indicator that shows the difference between the greatest and the lowest angle of the coils. When this difference exceeds the tolerance set in the corresponding control, this message is shown.



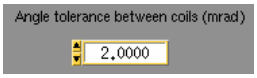
3. **SHOW RESULTS:** These controls are used for recovering results saved previously. By the time that results are saved, the lists get updated and new files storing them can be seen in the lists. Selecting a file from the "One coil" list, only results from this concrete coil (the one referred to the position that follows the word 'SECT') are shown. Once all the measurements have been carried out from all the coils in a mole, and their results have been saved, a new file is created in the "Set of Coils" list. With them, results from all the coils inside the mole will be displayed. The two controls on the top are used for confirming the selection in both cases.



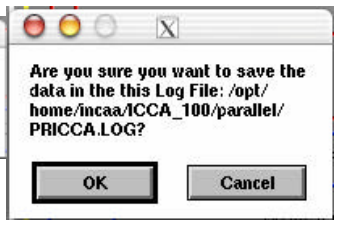
4. **SAVE CURRENT RESULTS:** Control, not visible when files are loaded but visible in other case, with which temporary parallelism files (*.TPF files) are created. These files, storing the angles of the fields of the coils, are available in the "One coil" list, once they are created, to facilitate the recovering of them.



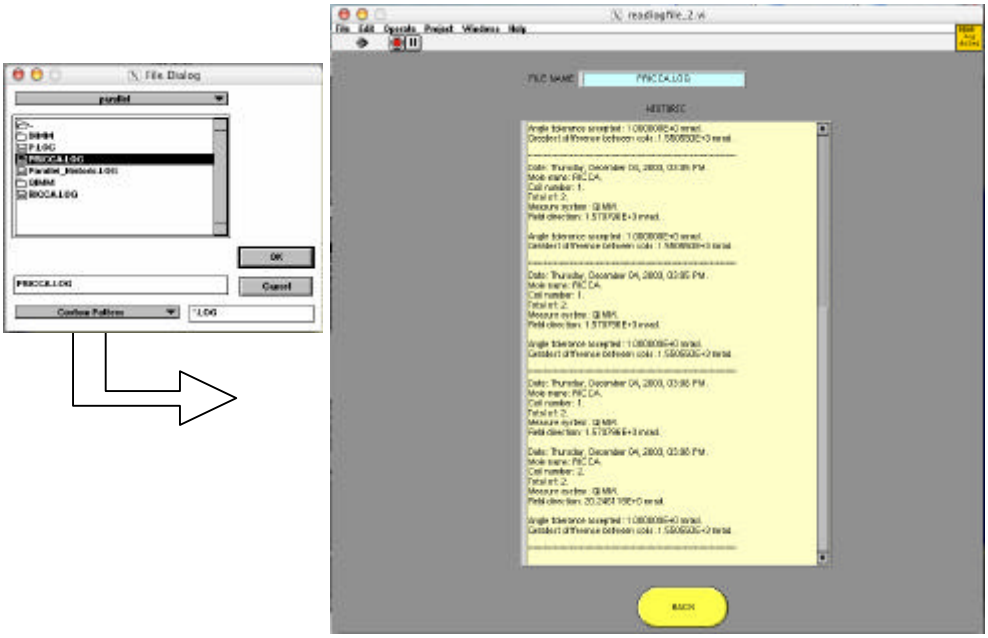
5. **ANGLE TOLERANCE:** This numerical control sets the maximum difference (in mrad) acceptable between angles of the coils.



6. **LOG FILE:** These two controls allow the user to save the summary of the results (this operation should be done after loading a file from the "Set of coils" list) in a *.LOG file or read them. When someone wants to save some information, the user is asked to validate the action twice. In other case, if it is desired

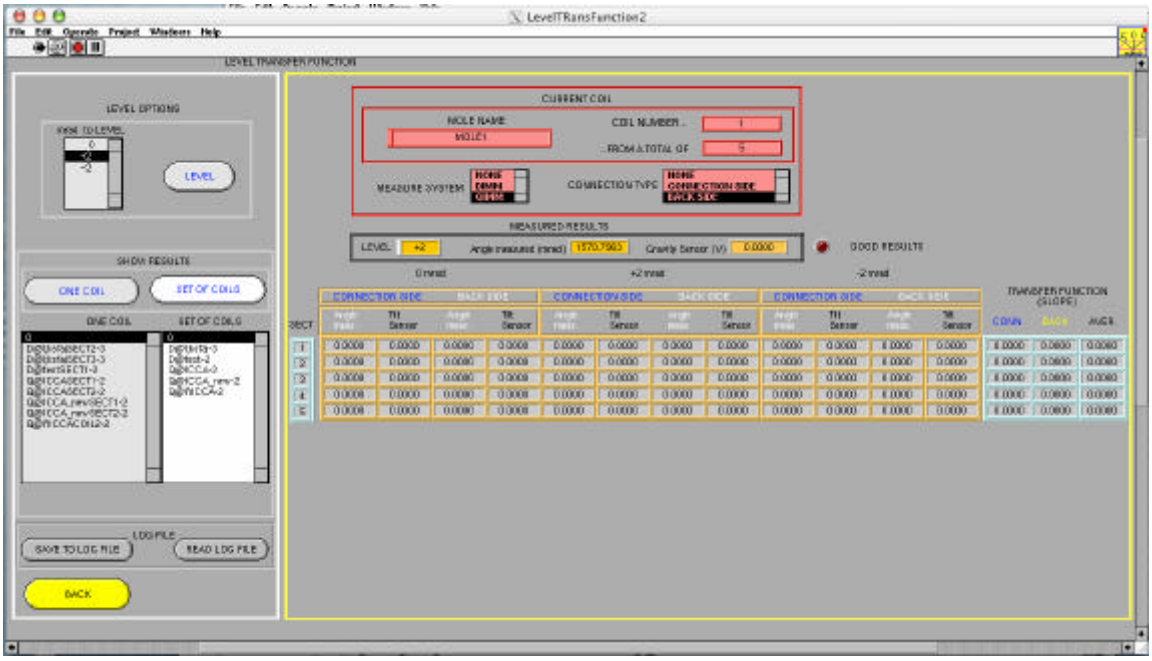


to read information previously saved, the windows that will appear are these ones (Note that all the LOG files name refered to the parallelism begins with a 'P')



7. **BACK:** This control finishes the execution of the VI and returns the control to the previous panel.

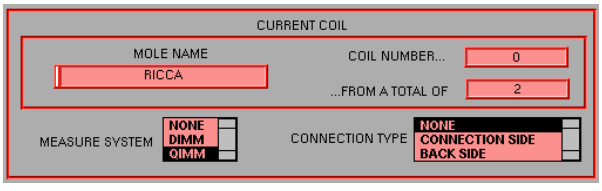
- LEVEL TRANSFER FUNCTION MEASUREMENT



This panel is for the level analysis. The linearity of the Tilt Sensor can be checked periodically with the calculation of the level transfer function parameter. If this panel is launched with the intention of making a DIMM measurement, this message will remind the user to connect the correct shaft with the corresponding tilt sensor since there will be two different ones:

To achieve this final parameter, many measurements must be made. The panel is structured as follows:

1. **CURRENT MOLE:** As explained earlier, these fields intend to provide information about the mole selected, the measure system and the type of connection used:



e. **MOLE NAME:** The name of the mole that was used for the measurement.

f. **COIL NUMBER:** This is to identify to which coil inside the mole the measurement is related. If it is zero, then it means that a file from a "set of coils" list has been loaded (and, hence, all of the coils are selected).

g. **…FROM A TOTAL OF:** The total number of coils that composes the mole.

h. **MEASURE SYSTEM:** Shows which system was, or should have been, used for the measurement with the current mole.

i. **CONNECTION TYPE:** Shows how was connected the mole during the measurement.

2. **MEASURED RESULTS:** It is composed of three indicators and one LED that show the results obtained in the last measurement:

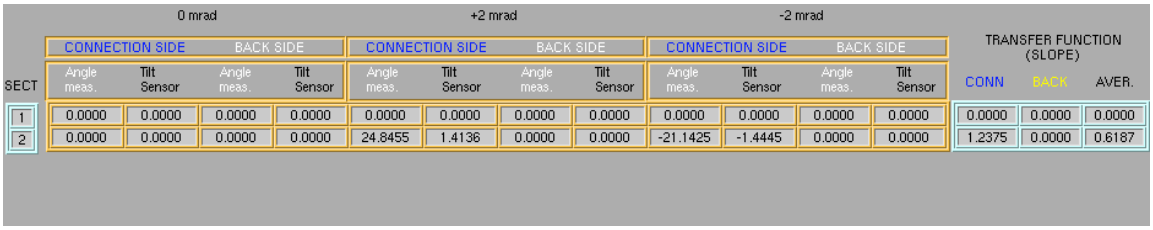
a. **LEVEL:** Indicates the expected value to which the mole should have been leveled.

b. **ANGLE MEASURED (mrad):** This is the real value to which the mole was leveled. Ideally, it should value exactly the same as the LEVEL field.

c. **Gravity Sensor (V):** This is the value extracted from the Tilt Sensor in Volts.

d. **RESULTS' LED:** Indicates the reliability of the results obtained. It is off if they are, in principle, ok and on when there was a problem during the measurements. In that case, the reliability of the data is not assured so, it is better not take into account them.

3. **RESULTS:** This is structured in three parts:

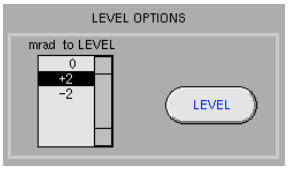


   a. **SECTOR:** There will appear as many rows as coils there are into the selected mole.

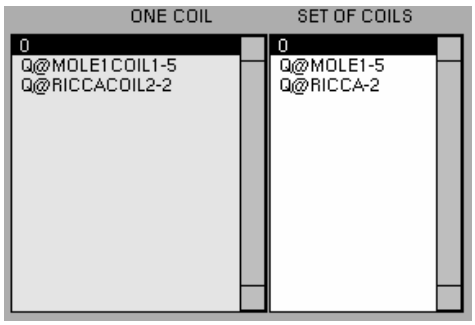
   b. **RESULTS TABLE:** This table contains all the intermediate values needed to achieve the level transfer function. It is structured in 3 parts (as many as possibilities to level: 0, +2 and –2). Each one is divided in two more parts, one for each kind of connection (Back and Connection side). Finally, each of these two parts are as well divided in two more ones (columns) where the results from the tilt sensor and from the measured angle are visible. So, depending on which coil of the mole, which was the leveling and the kind of connection in the last measurement, the corresponding results from "Measured results" will be displayed on the correct fields in the table.

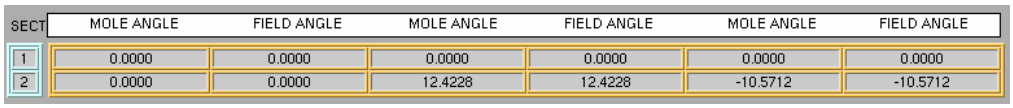
   c. **TRANSFER FUNCTION (SLOPE):** This parameter is the slope of a straight line calculated from the tilt sensor reading and the measured angle in three different level values. The first column shows the slope of the straight line obtained from the connection side measurements, the second one from the back side ones and the third one the average of these two (for each coil); in other words, the important parameter it was being looked for.

4. **LEVEL OPTIONS:** It is composed by a list in which it can be selected the value to which it is desired to level the mole. By clicking, then, on the "level" button, the measurement process begins with the selected leveling.

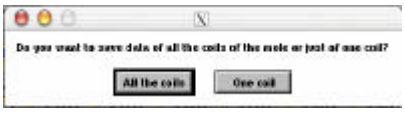


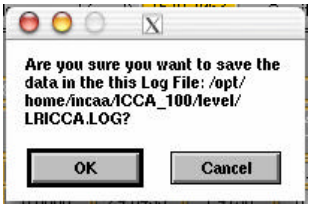
5. SHOW RESULTS: As in previous panels, these controls are used for recovering previously saved results. By the time those results are saved, the lists get updated and new files storing them can be seen in the lists. Selecting a file from the "One coil" list, only results from this concrete coil are shown. Once all the measurements have been performed to the totality of coils in a mole and their results have been saved, a new file is created in the "Set of Coils" list. With it, results from all the coils inside the mole will be displayed. The two controls on the top are used for confirming the selection in both cases. A new control can be seen on the bottom with which more information about the results can appear on the panel (Mole angle means the average between a connection and a backside result. Field angle means the semi difference between them):



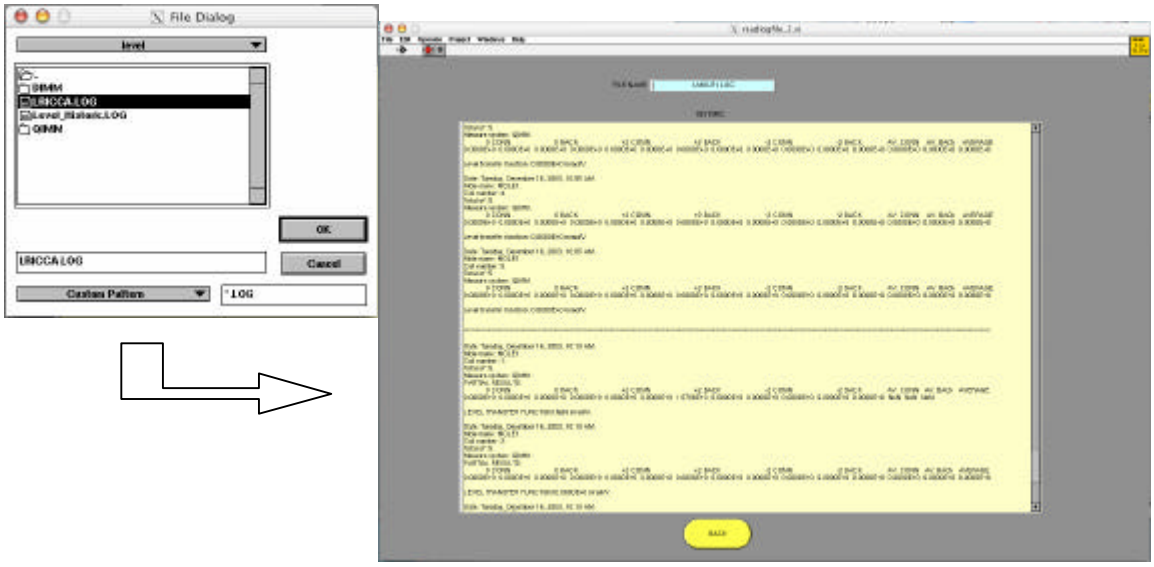


6. LOG FILE: These two controls allows the user to save the two tables with the results in a *.LOG file or read them. When the "Save to LOG file" button is pressed, the user is asked if data to be saved are from one coil or from the whole of coils. Then, the action must be validated twice. If previously saved information is desired to be read, these windows will appear (Note that all the LOG files name refered to the leveling begins with an 'L'):





7. **SAVE RESULTS:** Once the results are shown in the tables and the user agrees them, thanks to this control, files with these data can be created. Later, they are available in the lists explained earlier to recover them.



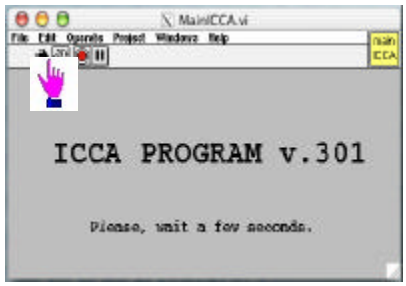
8. **BACK:** This button closes the VI in course and the flux of the program returns to the previous panel.

HOW TO MAKE MEASUREMENTS

This part of the manual will guide the user to know the steps to follow from the initial panel of the program until the measurement is finished and data is saved. To make it more understandable, an example will be followed.

Let's imagine that it is needed to check if the tilt sensor inside a concrete mole will be working in the same way as three months later and after using it regularly. Then, a comparison between the level transfer functions in three months time will be needed. It will be used the measuring coil only; this means, the coil number 1 inside the mole.

The first thing to do is reaching the path where the main VI remains (see next chapters). Once it has been found, click twice on it and wait until this panel appears. Then, it is time to launch the application by clicking on the run button.

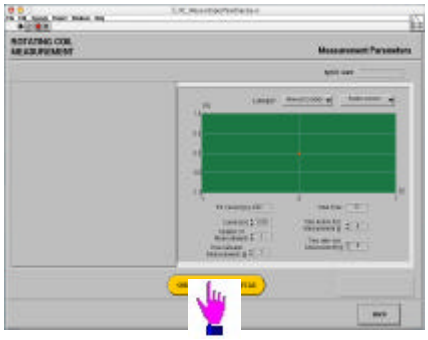


After running the application, the next thing to be done is creating the configuration file in order to start the measurements. For that reason, one should click on the "MMP-CREATE CONFIG FILE" button.

Now, a *.CCS file for the mole and as many *.txt files as coils there are inside the mole are needed. To create them, the "Create Coil Description" should be pressed.

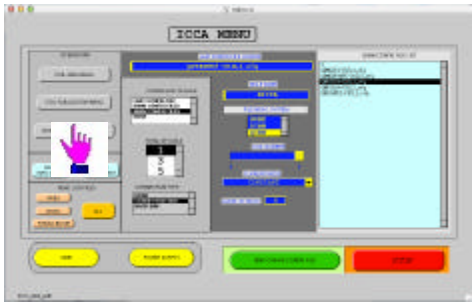
Once the panel has appeared, fill in all the fields carefully ('Mole name' and 'Coil number', above all since the names of the files will contain them): Field parameters, Coil Parameters and Coil coefficients. Create the .CCS file by clicking on the "SAVE coilcoef SETTING" button once and the "CREATE FILE" button for the *.txt files for each coil changing the corresponding settings (coil number…) for each coil. In this concrete example, after doing this, the files generated are: MOLE1.CCS, MOLE1-COIL1.txt, MOLE1-COIL2.txt, MOLE1-COIL3txt, MOLE1-COIL4.txt and MOLE1-COIL5.txt.

Now it is time to create the configuration files (one for each coil). Click on "Load Coil Data" button and select MOLE1-COIL1.txt to start with the first coil, for instance. Fill in Measurement parameters, Amplifier Parameters, Integrators Selector and click on the "Create Configure File" button to save the first part of the *.CFG file.



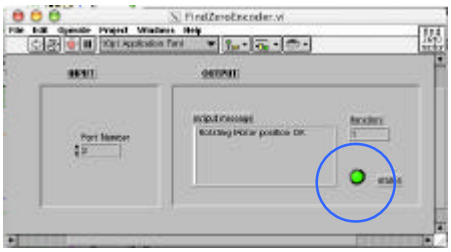
After this, one must enter the characteristics of the current during the measurement of the first coil to be set to the magnet: a cycle of current, constant, manual, value, polarity, number of measurements… Once the parameters are chosen, click on "Create Configure File" and the first one will be saved. Repeat the process to create the rest of them.

Depending on the measurement system selected while creating the files, those will appear in the DIMM list or in the QIMM one. In this case, it is being used a QIMM system. Select the file Q@MOLE1-COIL1.cfg, the maximum number of coils (five), the type of connection (connection side) and everything will be ready for starting the measuring process. To analyze the Level Transfer Function, this button must be pressed.

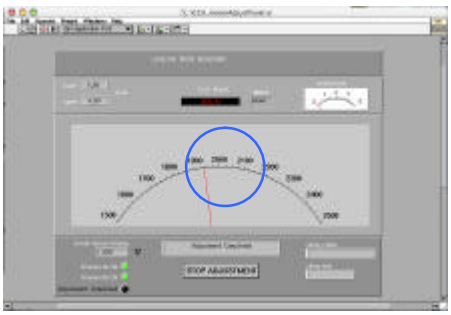


Then, this screen appears so that the level value is selected. For instance, +2 mrad will be chosen and, after clicking on the "level" button, the leveling process will start. Note that all the information referred to the mole that has been selected is displayed on the corresponding fields.

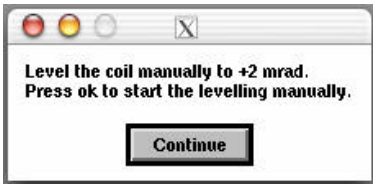
And it starts with the panel that shows how the rotating motor looks for the correct position to achieve valid measurements. Once this position is achieved, the LED turns green. That means that the leveling process is ready to start.



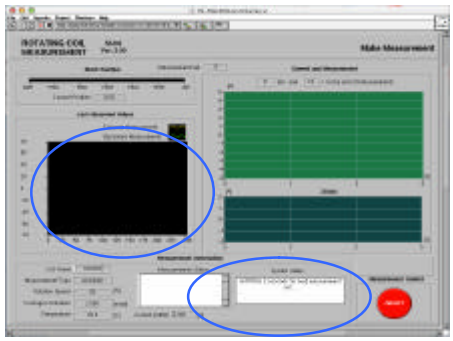
It can be seen how the needle approaches the value selected (+2 mrad) and how the adjustment is finished when it remains stable between the limits (located on the top left of the panel). It is important to note that this automatic level procedure is possible because a QIMM system is being used. In some cases working

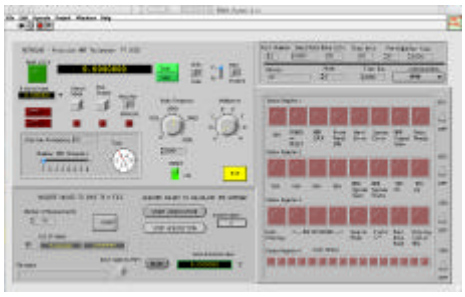


with a DIMM system, the leveling process MUST BE DONE BY HAND. The message will indicate this:

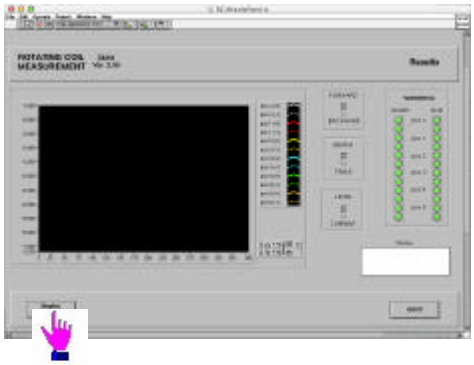


The next step is the measurement itself. The power supply sources the selected current to the magnet via GPIB (if it was not manual current) and the rotating motor starts to move in a forward direction while the integrators acquire the data. When it is finished, the motor moves to the other direction and does the same. This process is repeated as many times as measurements have been selected while creating the *.cfg file. For each measurement, the flux is represented (for forward and backward) in the graphic. After the x measurements, if there have not been problems, a quick analysis is done. If the tilt sensor's values are too different at the beginning and at the end of the measuring process, it starts again. If the field angle obtained in each measurement varies too much between each other, the set of measurements will also start again. After three failed tries the measurement is aborted and the results have no validity. In the fields on the bottom, it can be seen which is the mole involved in the measurement, temperature… In case of having clicked on Coil Area Measurement, the NMR panel will periodically appear at the beginning and at the end of each measurement to get an average value of the conrete measurement. The locked values must be acquire with the buttons start and stop acquisition. To go on with the process click on exit, after checking in the display that the value calculated is valid.

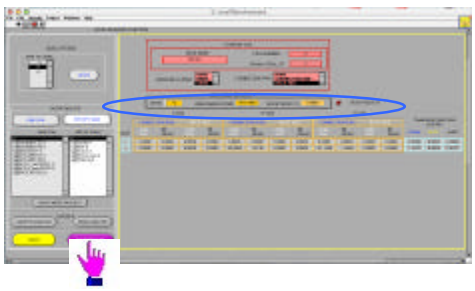


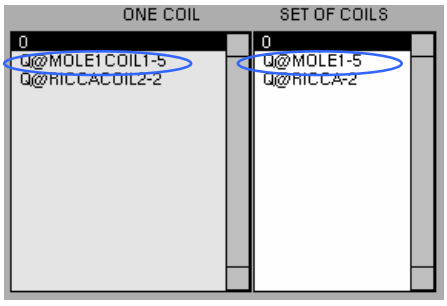


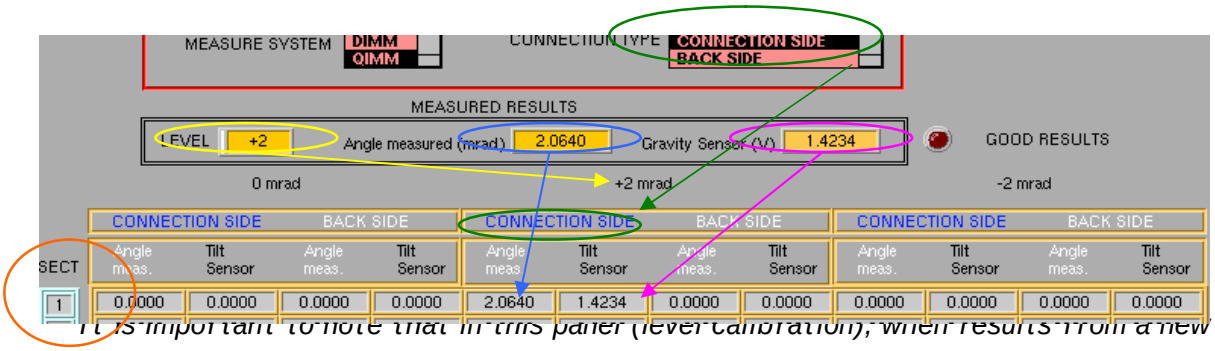
Later, some general results can be seen in this panel. It can be checked if the current has correctly sourced the magnet, if there has been differences between forward and backward… If it is needed seeing more detailed results, click on the appropriated button. Otherwise press the "BACK" one to analyze them.



When this panel appears again, it will be seen how the fields in "Measured Results" will be filled in with the average results from the measurements. (Also note that now it has appeared a new button for saving the data in a file). If during the measurement process there has been no problems (there was no need to abort because there was no warnings or errors) the LED will be off. If it is on, it means that the values are not reliable enough and the panel should be closed without saving the data in order to start again. Let's imagine everything has carried out successfully, then, after checking that the results are acceptable (in case of doubt, partial results can also be checked) they should be saved in a file by clicking on the purple button. Automatically, a new name in both lists will be shown*. These names refer to a file where, every time new results from the same mole are saved, all data needed will be stored. By selecting them we will be able to see data from the first coil (if it is chosen Q@MOLE1COIL1-5) or from the five ones (with Q@MOLE1-5). If it is selected the first one, the following data will be displayed:

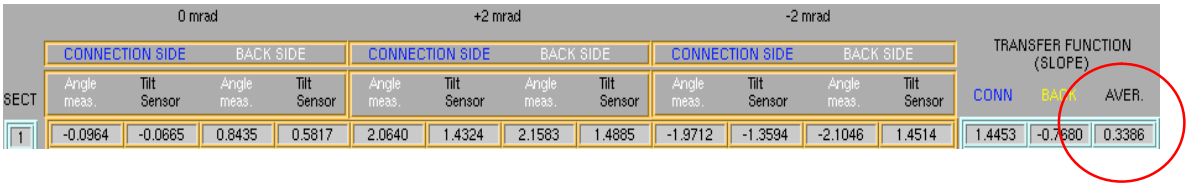




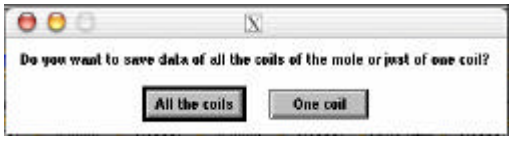


It is important to note that in this panel (level calibration), when results from a new mole are saved, the two lists are updated at a time with new different file names (Q@MOLE1COIL1-5 and Q@MOLE1-5 in this case) whereas in the other calibration panels (for parallelism or area), only the "One Coil" list is updated. Just when all the files referring to the same mole are created in this list, the new file on "Set of Coils" will be available.

If all this is repeated for all the level values and for both types of connections (for the first coil), finally, the first row will be completed and, hence, it will be achieved the parameter it was needed: the level transfer function.



Once this parameter has been obtained, it is time to save it in a *.LOG file. For this purpose, one has to click on "Save to log file" and confirm the selection. As we are only interested in the first coil, we will select only "One coil" (the one that can be read on the name of the file, number 1 in this case). Loading the file LMOLE1.LOG, one can find information such as the date when this file was last saved, the name of the mole, the number of the coil to which the results are referred, the total number of coils that compose this mole and the measurement system used:



This can be considered only the end of the first step of the calibration since these results cannot still be compared to previous ones in order to check their evolution. What can be done is check the Mole Angle and the Field one. The Field Angle should be always 0 or almost 0 (if the bench is stable) and the Mole Angle, ideally, should be equal to the value the mole was pretended to level.

SECT	MOLE ANGLE	FIELD ANGLE	MOLE ANGLE	FIELD ANGLE	MOLE ANGLE	FIELD ANGLE
1	0.0000	-0.0964	2.1111	-0.0472	-2.0379	0.0667
2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Some time later, these sorts of measurements and results obtained must be repeated and, only afterwards, there will be enough data to take decisions. Let's imagine this procedure has been followed and the following file has been updated with this final result:

FILE NAME LMOLE1.LOG

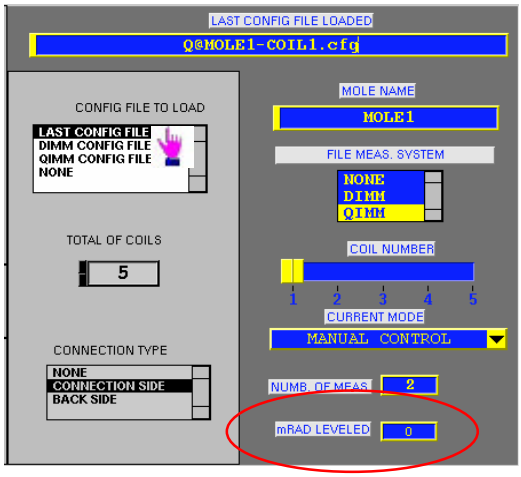
HISTORIC

```
Date: Tuesday, December 16, 2003, 01:01 PM.
Mole name: MOLE1.
Coil number: 1.
Total of: 5.
Measure system: QIMM.
PARTIAL RESULTS:
      0 CONN          0 BACK          +2 CONN         +2 BACK         -2 CONN         -2 BACK       AV. CONN AV. BACK AVERAGE
-96.4000E-3 -66.5000E-3 96.4000E-3 66.5000E-3 2.0640E+0 1.4324E+0 2.1583E+0 1.4885E+0 -1.9712E+0 -1.3594E+0 -2.1046E+0 -1.4514E+0 1.4453E+0 1.4500E+0 1.4476E+0

LEVEL TRANSFER FUNCTION: 1.4476E+0 mrad/V.

**********************************************************************************************************************************************************

Date: Thursday, March 5, 2004, 11:13 AM.
Mole name: MOLE1.
Coil number: 1.
Total of: 5.
Measure system: QIMM.
PARTIAL RESULTS:
      0 CONN          0 BACK          +2 CONN         +2 BACK         -2 CONN         -2 BACK       AV. CONN AV. BACK AVERAGE
-48.0000E-3 -33.1200E-3 0.8435E+0 0.5817E+0 1.8767E+0 1.2949E+0 2.0598E+0 1.4212E+0 -2.1019E+0 -1.4503E+0 -2.0446E+0 -1.4107E+0 1.4632E+0 1.4240E+0 1.4436E+0

LEVEL TRANSFER FUNCTION: 1.4436E+0 mrad/V.

**********************************************************************************************************************************************************
```

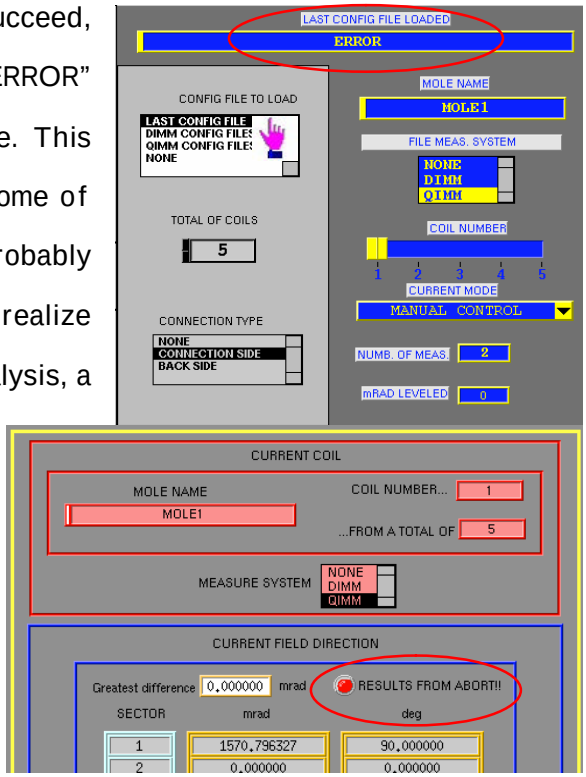
As the difference between both parameters is not really important, it can be said that there is not need to calibrate the gravity sensor inside the mole and we can trust in its reliability.

Some results from certain measurements can be sometimes useful for different types of calibrations. For instance, a measurement used for calculating the Level Transfer Function is finished (data has been saved) and the flow of the program is returned to

the main menu. Once there, before selecting a new measurement for this purpose (Level Transfer Function calculation), the first choice in the list "Config File to Load", **Last Config File,** can be selected. Doing this, there will not be new measurements in order to achieve results since with this selection it is assumed that they are already obtained and there is no need to repeat them. As it can be seen, the mole was leveled to 0 mrad. So, the results obtained in the last measurement could be acceptable for the parallelism calibration. If after this, the parallelism calibration panel is launched, the results will be perfectly shown in their corresponding fields.

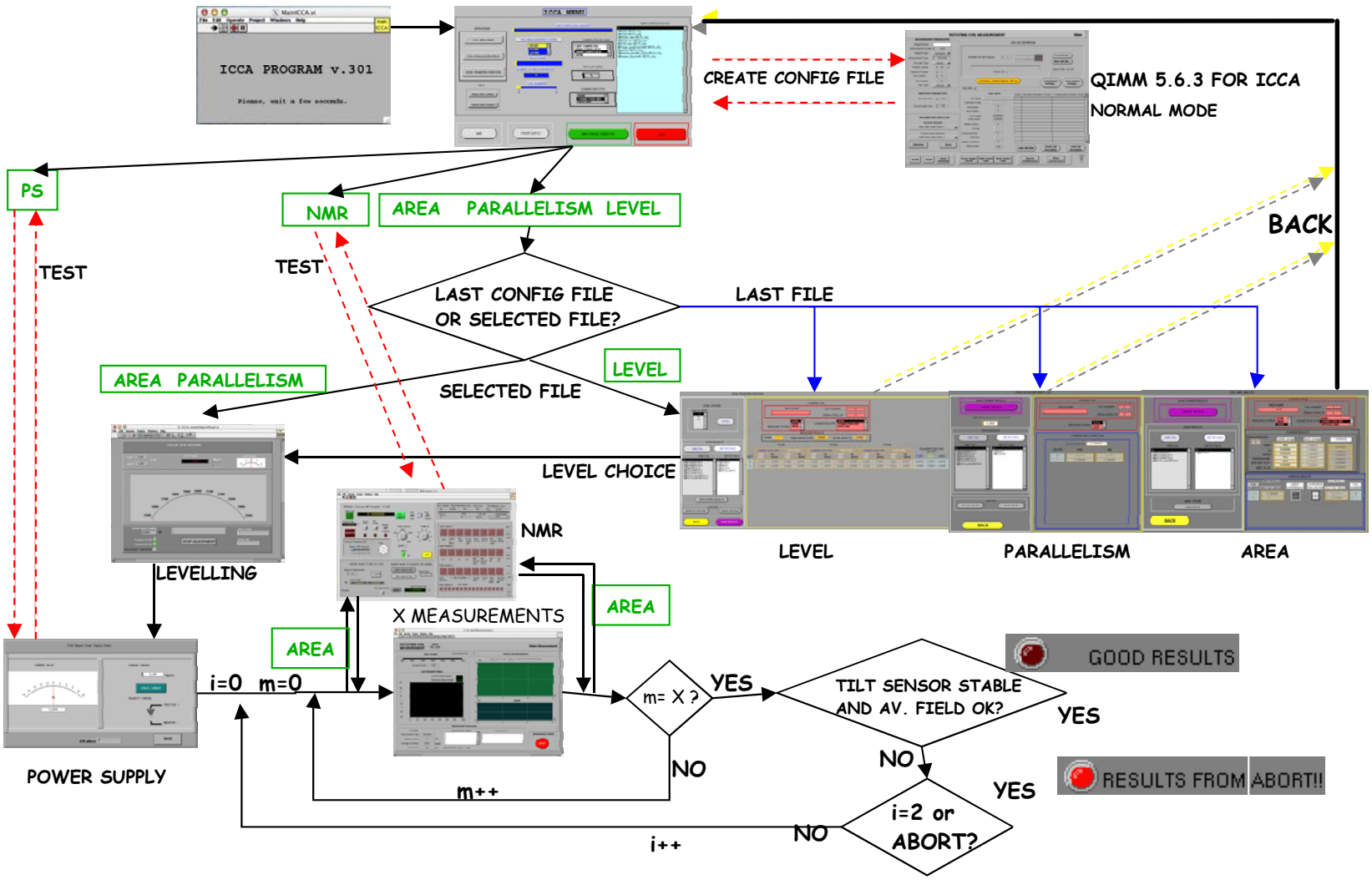


In case the last measurement did not succeed, when one selects the **Last Config File,** "ERROR" will be visible instead of an existing file. This means that the procedure has failed in some of its steps and, hence, the results are probably incorrect. In case the user does not realize about it and decides to go on with the analysis, a red LED on the top of the results will warn about the reliability of them. In this concrete case, it is recommended not to save them:



In the next sheet, there is a flow chart with which the user can have a generic view (not all the appearing screens are shown there) of the ICCA application and of the steps to follow to succeed in the use of it.

ICCA'S FLOW CHART



FILES' PATHS AND DISTRIBUTION

/opt/home/incaa/config/

- ICCAlevelsetup.cfg
- ICCAMeasRestrictions.cfg

/opt/home/incaa/config/ICCA/

- FORMAT.cfg
- LastCFGfile

/opt/home/incaa/config/ICCA/DIMM/

- *.cfg

/opt/home/incaa/config/ICCA/QIMM/

- *.cfg

/opt/home/incaa/database/ICCA/

- QIMMcoil-number.txt
- DIMMcoil-number.txt
- info_sheet.LOG

/opt/home/incaa/database/ICCA/area/

- *.LOG

/opt/home/incaa/database/ICCA/area/DIMM/

- *.CAL
- *.TAF

/opt/home/incaa/database/ICCA/area/QIMM/

- *.CAL
- *.TAF

/opt/home/incaa/database/ICCA/level/

- *.LOG

/opt/home/incaa/database/ICCA/level/DIMM/

- *.LCF

/opt/home/incaa/database/ICCA/level/QIMM/

- *.LCF

/opt/home/incaa/database/ICCA/parallelism/

- *.LOG

/opt/home/incaa/database/ICCA/parallelism/DIMM/

- *.TPF
- *.PCF

/opt/home/incaa/ICCA/database/parallelism/QIMM/

- *.TPF
- *.PCF

/opt/home/incaa/database/coildir/

- **.txt*
- **.CCS*

TYPE OF FILES

***.cfg**

These files are needed for the execution of the measurements. The format of the configuration names is the following:

'X'@'mole_name'COIL'Y'.cfg

'X' → Q if QIMM system. 'X' → D if DIMM system.

'mole_name' → name of the mole.

'Y' → number of the coil inside the mole.

e.g.:

- Q@Taupe4#QUAD-COIL2.cfg
- D@Mole1_new-COIL1.cfg
- Q@RICCA-COIL1.cfg

This last one contains the next information:

/opt/home/incaa/database/coildir/RICCA-COIL1.txt
test
2
0
0
2
50
1
0
2
0
non

0

2

3

FORMAT.cfg

This concrete file contains the format of the configurations files used for ICCA:

COIL DATA FILE	(ARRAY OF PATHS)
MAGNET NAME	(STRING)
MEASUREMENT-SYSTEM	(INDEX)
MAGNET_TYPE	(INDEX)
MEASUREMENT_TYPE	(INDEX)
ENCODER_TYPE	(INDEX)
ROTATION_SPEED	(INTEGER)
RUN_TYPE	(INDEX)
CURRENT	(INTEGER)
PS_CONTROL	(INDEX)
CYCLE_NAME	(STRING)
CURRENT_TYPE	(INDEX)
NUMBER_MEASUREMENTS	(INTEGER)
TIME_BETWEEN_MEAS	(INTEGER)

ICCAMeasRestrictions.cfg

This file contains three values. The angle biggest difference between coils, the tilt reading biggest difference between the beginning and the end of one measurement and the tilt reading biggest difference between the beginning and the end of the whole measurements. If these values are exceeded after the measurements are over, they are automatically restarted.

ICCAlevelsetup.cfg

This file stores the leveling settings used in ICCA. That means the angle to turn in each range, the value of the ranges, the limits of acceptance, the delay time before the leveling finishes…

***.txt**

These are the previous files before the creation of *.cfg files. There must exist as many *.txt files of the same mole as coils inside it. The information stored in them is related to each of these coils. The names' format and their content are:

'mole_name'-COIL'Y'.txt

'mole_name' → name of the mole.

'Y' → number of the coil inside the mole.

e.g.:

- MOLE1-COIL1.txt
- MOLE1-COIL2.txt

This lat one contains:

Coil name	MOLE1
Calibration date	0000000
Head number	0
sector number	2
Length	0.749900
Center offset	0.000000
Number of turns	400
Coil side	0.000000

Compensated rank 0

Cold warm

Number of coeffs 15

n	Kn Abs		Kn Comp	
	real	im	real	im
1	2.445414E+0	0	554.586000E-3	0
2	4.000000E+0	0	2.000000E+0	0
3	6.000006E+0	0	3.000003E+0	0
4	8.000022E+0	0	4.000011E+0	0
5	10.000056E+0	0	5.000028E+0	0
6	12.000111E+0	0	6.000056E+0	0
7	14.000194E+0	0	7.000097E+0	0
8	16.000311E+0	0	8.000156E+0	0
9	18.000467E+0	0	9.000233E+0	0
10	20.000667E+0	0	10.000333E+0	0
11	22.000917E+0	0	11.000458E+0	0
12	24.001223E+0	0	12.000611E+0	0
13	26.001589E+0	0	13.000795E+0	0
14	28.002023E+0	0	14.001011E+0	0
15	30.002528E+0	0	15.001264E+0	0

Offset encoder 0.000000

QIMMcoil-number.txt and DIMMcoil-number.txt

These special files store the relation between the name of the moles and the total number of coils inside them. They are updated the first time a mole is going to be calibrated, when the user entries this last parameter in the front panel. The next time a mole already used is selected, the total number of coils will be recovered from these files. Their contains and format are:

Name_of_the_mole-Total_Number_Of_Coils

Taupe4#QUAD-5

Mole1_new-3

*.CCS

These files store the coefficients settings of the moles (but not the values of the coefficients). They can be considered a summary of the *.txt files explained above. In fact, they contain very similar information. In addition, these files hold the value of the coil areas and the gains for absolute and compensated measurements. The format of their names is:

'mole_name'.CCS

'mole_name' → name of the mole.

e.g.:

- MOLE1.CCS
- Taupe_dipole#14.CCS

*.LOG

These files are the outputs of the calibration procedure. They store the results of the different types of calibrations (historic) and interesting or specific information about them. It exists three *.Log files per mole, one for each type of calibration, and a main one for general purpose. This last one and its format is:

info_sheet.LOG

Tue Nov 18 18:56:42 2003

This is an useful way to save and keep in a compact way information, concrete situations, errors generated, bugs detected… that can be useful not only for future uses but also for future users.

AREA LOG FILES

Files generated as a result of area calibrations. The format of the names is:

A'mole_name'.LOG

e.g.:

- ARICCA.LOG

Date: Wednesday, December 03, 2003, 06:18 PM.
Mole name: RICCA.
Coil number: 1.
Total of: 2.
Measure system: QIMM.

OLD AREA VALUES:

COIL 1: 3.641940E+0 m2.
COIL 2: 445.414000E-3 m2.

NEW AREA VALUES:

COIL1: 5.783920E+0 m2.
COIL2: 445.414000E-3 m2.

PARALLELISM LOG FILES

Files generated as a result of parallelism between coils calibrations. The format of the names is:

P'mole_name'.LOG

e.g.:

- PRICCA.LOG

Date: Thursday, December 04, 2003, 03:06 PM.
Mole name: RICCA.
Coil number: 1.
Total of: 2.
Measure system: QIMM.
Field direction: 2.050796E+0 mrad.

Date: Thursday, December 04, 2003, 03:06 PM.
Mole name: RICCA.
Coil number: 2.
Total of: 2.
Measure system: QIMM.
Field direction: 20.246119E+0 mrad.

Angle tolerance accepted: 1.000000E+0 mrad.
Greatest difference between coils: 18.195320E+3 mrad.

LEVEL LOG FILES

Files generated as a result of level calibrations. The format of the names is:

L'mole_name'.LOG

e.g.:

- LRICCA.LOG

Date: Tuesday, December 16, 2003, 01:01 PM.

Mole name: RICCA.

Coil number: 1.

Total of: 5.

Measure system: QIMM.

PARTIAL RESULTS:

0 CONN	0 BACK	+2 CONN	+2 BACK	-2 CONN	-2 BACK	AV. CONN	AV. BACK	AVERAGE
-96.4000E-3	-66.5000E-3	96.4000E-3	66.5000E-3	2.0640E+0	1.4324E+0	2.1583E+0	1.4885E+0	-1.9712E+0	-1.3594E+0	-2.1046E+0	-1.4514E+0	1.4453E+0	1.4500E+0	1.4476E+0

LEVEL TRANSFER FUNCTION: 1.4476E+0 mrad/V.

****

Date: Thursday, March 5, 2004, 11:13 AM.

Mol name: RICCA.

Coil number: 1.

Total of: 5.

Measure system: QIMM.

PARTIAL RESULTS:

0 CONN	0 BACK	+2 CONN	+2 BACK	-2 CONN	-2 BACK	V. CONN	AV. BACK	AVERAGE
-48.0000E-3	-33.1200E-3	0.8435E+0	0.5817E+0	1.8767E+0	1.2949E+0	2.0598E+0	1.4212E+0	-2.1019E+0	-1.4503E+0	-2.0446E+0	-1.4107E+0	1.4632E+0	1.4240E+0	1.4436E+0

LEVEL TRANSFER FUNCTION: 1.4436E+0 mrad/V.

****

***.CAL**

These files are generated by the area calibration and store information (new surface value, NMR lecture, Maximum Flux…) related to a connection side measurement, back side and the average of them. The names' format is:

'X'@'mole_name'COIL'Y'-'Z'.CAL

'X' → Q if QIMM system. 'X' → D if DIMM system.

'mole_name' → name of the mole.

'Y' → number of the coil inside the mole.

'Z' → total number of coils inside the mole.

e.g.:

- Q@RICCACOIL1-2.CAL
- Q@RICCACOIL2-2.CAL

***.TAF**

These are temporary files that contain part of the information stored in *.CAL files. The names' format is similar to the previous ones but with an extension at the end:

'X'@'mole_name'COIL'Y'-'Z'_'SIDE'.TAF

'SIDE' → CONN if connection side. 'SIDE' → BACK if opposite side.

e.g.:

- Q@RICCACOIL1-2_CONN.TAF
- Q@RICCACOIL2-2_BACK.TAF

***.LCF**

These are numerical files (a 'Z'x15 table) where the information generated by the level calibration is saved. The format of this type of files is:

'X'@'mole_name'COIL'-'Z'.LCF

'X' → Q if QIMM system. 'X' → D if DIMM system.

'mole_name' → name of the mole.

'Z' → total number of coils inside the mole.

e.g.:

- Q@RICCACOIL2.LCF
- D@taupe#2COIL5.LCF

***.PCF**

These type of files are the ones that store the results (the field direction of all the coils inside the mole) concerning to the calibration of the parallelism between coils. This is their format:

text'X'@'mole_name'COIL'-'Z'.PCF

'X' → Q if QIMM system. 'X' → D if DIMM system.

'mole_name' → name of the mole.

'Z' → total number of coils inside the mole.

e.g.:

- Q@RICCACOIL1-2.PCF

- D@taupe#2COIL3-5.PCF

***.TPF**

These are temporary files that contain part of the information stored in *.TPF files (only the one related to the refered coil). The names' format is exactly the same as to *.CAL files:

'X'@'mole_name'COIL'Y'-'Z'.TPF

'X' → Q if QIMM system. 'X' → D if DIMM system.

'mole_name' → name of the mole.

'Y' → number of the coil inside the mole.

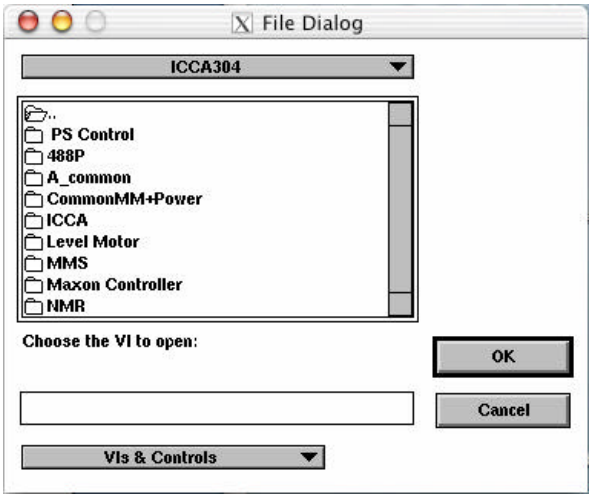
'Z' → total number of coils inside the mole.

e.g.:

- Q@RICCACOIL1-2.TPF
- Q@RICCACOIL2-2.TPF

NEW LIBRARIES AVAILABLE

The final distribution of VI and libraries is that one. As we can see, there are nine different folders in the main one: ICCA304. Each of them hosts the libraries where there will be the VI used in the ICCA program. Most of them have been only updated with the new VI. These are:



~/PS Control/PS_control.llb

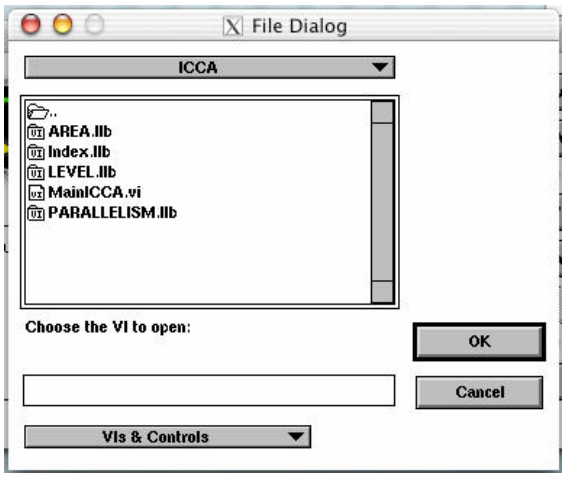
~/Level Motor/ICCA_level_Motor.llb

~/Maxon Controller/MMS_MOTOR.llb

~/NMR/NMR.llb

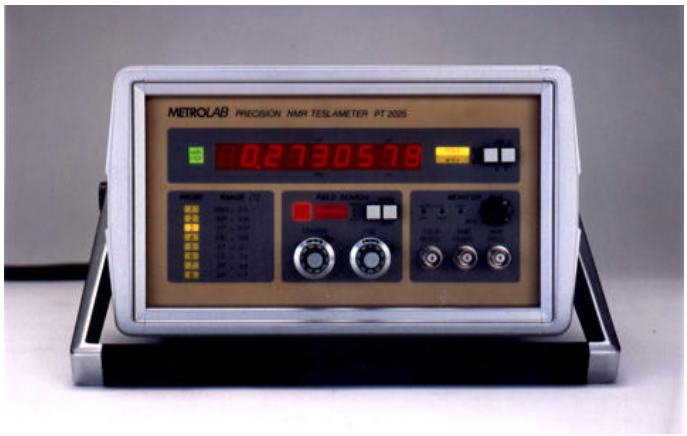
...

The new libraries created for the new front panels are inside the folder called ICCA. As it can be seen, there are four libraries and the main VI that runs the application.



APPENDIX 3.

NMR TESLAMETERS PT-2025 DATASHEET



The PT 2025 is a high precision, microprocessor controlled and fully programmable NMR Teslameter, especially suited for any application where rapid, fully automatic and very accurate measurements of magnetic fields are of primary importance, such as MRI, accelerator beam handling, magnetic sensors calibration, etc.

- Easy to use
- Automatic search and tracking on the full probe range (or ranges : Multiplexer)
- High reliability
- Fully programmable, directly remote controllable
- Possibility to drive an external 8 channels Multiplexer
- High precision, independently of temperature
- Field Regulation Option (RG 2040)

Field range: 0.011 to 13.7 Tesla

Resolution: 10-7T or 1Hz

Digital Interfaces: IEEE488 and RS 232C

Specifications

- **Measurement principle**: NMR (Nuclear Magnetic Resonance of protons 1H or deuterons 2H)

- **Field range**: 0.011 T* - 13.7 T
- **Absolute accuracy**: better than ±5 ppm (1H)
- **Relative accuracy**: better than ±0.1 ppm
- **Display** : 81/2 digits, Tesla or MHz
- **Resolution**: 10-7T or 1 Hz
- **Tracking rate**: max. 1%/sec
- **Time lag**: 17 ms. or less
- **Reading rate**: about 1/sec. or 10/sec
- **Reading**: 9 LED 11 mm Tesla or MHz
- **Temperature stability of the internatal frequency counter**: ± 0.5 ppm (5°C to 50°C)
- **Aging** (counter): 2 ppm/year

Interfaces

- IEEE 488 and RS 232C

All front panel functions are programmable:

- MHz or Tesla display reading
- Field Polarity setting
- Frequency setting
- Field Search and Lock
- External Multiplexer driving

Field Search and Lock

Auto mode

The PT 2025 sweeps the radio frequency over the whole range of the FINE potentiometer (typically ±5% of the COARSE setting).

Search mode

In this mode the microprocessor takes control of all the front panel commands rendering them inoperative. Simultaneously an automatic field search is activated. The entire range of the probe is scanned (from bottom to top) until the NMR signal is seen; at which point the PT 2025 "locks" on to the signal.

Noise and interference signals are detected and by-passed by the search algorithm.

Once the PT 2025 has "locked" on to a signal the search algorithm can follow the field over the whole probe range. When connected to a computer and with the aid of the probe multiplexer, the PT 2025 can be programmed to search for a field over several probes and to track it.

Outputs

Monitoring outputs (front panel)

- **Field modulation**: BNC
- **NMR signal**: BNC
- **NMR frequency**: BNC

Outputs (rear panel)

- **RF output to amplifier**: BNC
- **Power to amplifier**: LEMO 8 pins
- **Multiplexer**: LEMO 4 pins
- **IEEE 488** and **RS 232C**: standard connectors

General

- **Power requirement**: 40VA: 110/220 Volts 50/60Hz
- **Operating temperature**: 10° to 40°C
- **Stocking temperature**: -20° to 70°C, except 2H probes: 5° to 70°C
- **Magnetic environment**: 0.1 Tesla max. for main unit; 1 T for the Mux/Amplifier
- **Dimensions of PT 2025**: 260 x 1445 x 340 mm
- **Enclosure**: non magnetic
- **Weight**: 6,8 kg (15 lb)

Minimum Accessories required

- **Probe**(s) (10m length integral cable): 1062/1082 (Amplifier built-in) or Probe(s) (7m length integral cable): 1060/1080
- **Amplifier** 1030
- **Cable** 1010 to Amplifier 1030

Optional Accessories

NMR Field Regulation: RG 2040

The optional plug-in module RG 2040 is a major addition to the PT 2025 Teslameter. It provides closed loop long-term stabilization of magnetic fields and permits a full MPS (Magnet Power Supply) control.

- **High stability internal counter: HS 2060**

temperature coefficient: <±5 ppb/°C;

aging: <±2 ppb/day

- **Carrying case: CC 2020**

A light case for hand carrying a complete NMR Teslameter system.

- **8 channels Multiplexer with built-in Amplifier: MUX 2031**

For probes 1060 or 1080.

Requires cable 1011 to main unit (Does not require the Amplifier 1030)

- **8 channels Multiplexer : MUX 2030**

For probes 1062 or 1082.

For probes 1060 or 1080 it requires one Amplifier 1030 for each channel.

Requires cable 1011 to main unit

- **8 channel Multiplexer: MUX 2032**

Multiplexer of multiplexer: can multiplex up to 8 MUX 2030 or MUX 2031.

Allow a total of 64 NMR probes.

Requires cable 1015 to main unit and cable 1011 to MUX 2030 / 2031

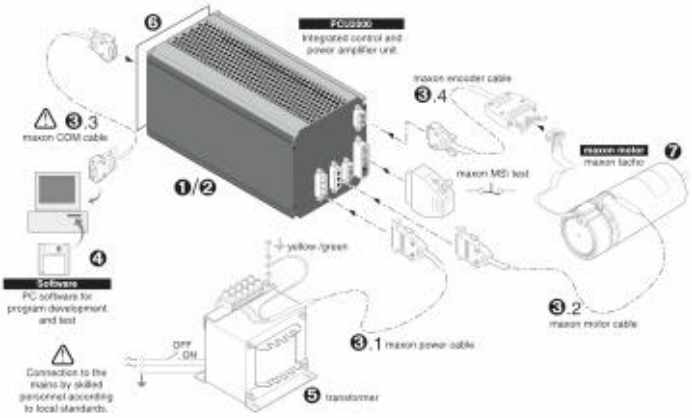
Requires modifications on the PT2025-4025. (Consult factory)

http://www.metrolab.com/Datasheet/20254025datasheet.htm

APPENDIX 4.

PCU 2000 MAXON MOTOR CONTROL DATASHEET

PCU 2000



169354, Set 1 contains:
169355, Set 2 contains:

	Partnumbers			Description:
❶	169352		1	1-Axis Positioning Controller, 5 A, 20-34 VAC or 24-48 VDC
❷	169353	1		2-Axis Positioning Controller, 2 x 5 A , 20-34 VAC oder 24-48 VDC
❸.1	134796	1	1	maxon power-cable (length 3 m)
❸.2	134797	2	1	maxon motor-cable (length 3 m)
❸.3	133367	1	1	maxon COM-cable (length 3 m)
❸.4	134795	2	1	maxon encoder-cable (length 3 m)
❹	133336	1	1	Software MPUI Vers.1, 3.5", documentation and user's manual included
The following accessories are not included in the set				
❺	108153	Trafo prim.: 230 V,		sec.: 34 VAC / 4 A
❻	108155	Trafo prim.: 230 V,		sec.: 34 VAC / 8 A
❽	169356	19" Front panel 3HE / 21TE, suitable to 1-Axis Positioning Controller, 169352		
❾	169357	19" Front panel 3HE / 28TE, suitable to 2-Axis Positioning Controller, 169353		
Recommended motor-encoder unit				
❼	44.032.000-00.09-237	maxon DC motor 2332.968-51.236-200 (see page 89) with Digital Encoder 110514		
❼	134971	maxon DC motor RE ⌀25 mm 118752 (see page 74) with Digital Encoder 110512		
❼	143849	maxon DC motor RE ⌀35 mm 118778 (see page 76) with Digital Encoder 110514		
❼	44.060.000-00.09-088	maxon DC motor 2260.813-51.216-200 (see page 99) with Digital Encoder 110514		
❼	44.060.000-00.09-097	maxon DC motor 2260.885-51.216-200 (see page 100) with Digital Encoder 110514		

Efficient, simple programming: the fast way to success

Axis initialisation:
HOME ..... search for machine zero point
DEF ORIGIN ..... define zero point
SET ORIGIN ..... define zero point temporarily
RST ORIGIN ..... reset to zero point
MOTOR ON/OFF ..... position control on/off
ERRCLR ..... reset error message

Program Control:
DELAY ..... time delay
WAITI ..... wait for input
WAITAX ..... wait for end of move
NOWAIT ON/OFF ..... wait during positioning on/off
EXIT ..... premature program stop
GOTO ..... program branch
IF..THEN..ELSE ..... conditional program branch
LOOP ..... program loop with counter
REPEAT..UNTIL ..... conditional program loop
WHILE..DO ..... conditional program loop
GOSUB ..... subroutine call

Interrupt functions:
ON ERROR GOSUB subroutine after error condition
ON INT..GOSUB ..... subroutine after interrupt

Motion commands:
VEL, CVEL ..... set speed
ACC ..... set acceleration
POSA, POSR ..... absolute/relative positioning
ORIGIN ..... move to zero point
INDEX ..... search for index pulse
CSTART, CSTOP ..... speed mode on/off
GETVEL ..... measure speed
SETVEL ..... set speed
MOTOR STOP ..... motion stop
MOVEON ..... continue motion

I/O commands
IN, INB ..... read inputs bit/byte
OUT, OUTB ..... set outputs bit/byte
PRINT ..... send data via maxon COM
INKEY ..... read data via maxon COM
APOS ..... read current position
CPOS ..... read set position
AXEND, STAT ..... read axes-/system status
TIME ..... read system time
GET, SET ..... read/set axis parameters

Performance Data

Technical data

- Supply voltage (Input): 20 - 34 VAC or 24 - 48 VDC
- Internally provided voltage: 24 - 48 VDC; 24 VDC / 1 A; 5 VDC
- Externally usable voltage: 24 VDC / 1 A
- Amplifier output current:
  Continuous current: 5 A
  Maximum current: 10 A
- Weight
  1-Axis PCU: 1600 g
  2-Axis PCU: 2100 g
- Size (W x H x D)
  with 19" front panel (Option)
  1-Axis PCU: 106.7 x 111 x 212 mm
  2-Axis PCU: 142.2 x 111 x 212 mm

Control Unit:

- 8 bit-microprocessor (24 MHz)
  + 1 co-processor per axis
- memory:
  32KB EPROM: operating system
  32KB RAM: user programs
  32KB EEPROM: program and parameter backup
- serial communication interface: RS232, 9600 Baud
- inputs / outputs:
  1 encoder-input per axis: complementary (RS422)
  1 input reference switch (zero position) per axis
  1 input limit switches
  8 digital inputs: high-active, optically isolated, filtered
  8 digital outputs: open-collector (100 mA), optically isolated, short circuit protected
  1 set value output per axis: +/- 10 V
- max. move: unlimited
- max. positioning distance:
  encoder with 500 CPR: 536000 rev.
  encoder with 1000 CPR: 268000 rev.
- max. path speed rate:
  encoder with 500 CPR: 18000 rpm
  encoder with 1000 CPR: 9000 rpm
- indicators: Power, Error, Move, Position

Amplifier:

- max. continuous output current: 5 A
- max. peak output current: 10 A
- inputs / outputs:
  1 DSV-input (disable power-stage, low-active)
  1 current monitor (analog) per axis
- trim potentiometers: peak current limitation
- indicators: Power, Error

Standalone-System:

- connectors: DSUB- male / female
- housing: 19" - plug in unit 3HE
- environmental conditions:
  storage temperature: -20 / + 70 °C
  relative humidity: yearly average without condensation < 75 %
  Operating temperature: 0 / 40 °C (free convection)

maxon motor control

Summary Positioning Control Units

Application Notes

maxon motor control

Choosing the positioning control unit:

Standalone-System

PCU 2000

- Point to point control unit
- 1-Axis positioning controller
- 2-Axis positioning controller
- For DC motors
- Continuous output current I_{cont} up to 5 A
- 8 digital inputs
- 8 digital outputs
- 19" rack compatible

Especially for standalone operation
Very simple programming,
only minimal programming knowledge necessary.
Typical applications:
Work equipment manufacturing and system automation tasks in special machinery, single applications up to small series.

Online-Commanding (PC or PLC)

MIP 10

- Point to point control unit
- 1-Axis controller
- Multiple axis systems by networking over serial data bus
- For DC motors
- Continuous output current I_{cont} up to 1.8 A
- 8 digital inputs
- 4 digital outputs

Operation with online commanding by PC or PLC
Programming knowledge necessary

Typical applications for DC motors up to 50 Watt:
Experimental setups
Work equipment and examination equipment manufacturing

MIP 50 / MIP 100

- Point to point control unit
- 1-Axis controller
- Multiple axis systems by networking over serial data bus
- Software configurable for DC motors and EC motors
- Continuous output current I_{cont} up to 5 / 10 A
- 8 digital inputs
- 6 digital outputs
- Eurocard format

Operation with online commanding by PC or PLC
Programming knowledge necessary

Typical applications for DC motors and EC motors up to 250 / 500 Watt:
Work equipment and examination equipment manufacturing
Machine tool industry

Important notes:

- **Standalone operation**
  Independent process cycle control without superior system.
  The process cycle must be programmed into the positioning control in advance.
- **Online commanding**
  Single motion and I/O commands from the process cycle control are transmitted to the positioning control by a superior system. For that purpose product specific commands are available.
- **Point to point control unit**
  Released by a motion command a complete path / time profile from point A to B will be generated. Usually a modification of the motion parameters (end point, acceleration, speed) is possible, also during the execution of the command.
- **Path generator**
  Internal calculation routine, which automatically calculates, taking the current position into consideration, end point, acceleration and speed in a certain pulse, new set value positions for the control circle.
- **Speed profile**
  Automatically calculated speed process during a motion. Usually a trapezoidal speed profile is used, which can be divided into three sub-ranges (constant acceleration, uniformed motion, braking).
  A gentler starting and brake behavior (without torque impacts) can be obtained by profiles with sinusoidal acceleration
- **Position detector**
  Digital encoder or linear measuring systems. Due to control-technical reasons an encoder which is directly mounted to the motor is preferable. With incremental encoders the current position is determined by the positioning control by continuing counting of the impulses.
  With the start-up of the system a reference run must be made on a defined point (index or reference switch) for absolute defined position.
- **Accuracy and resolution**
  As a result of the flank analysis of the signals from the position detector a four times higher resolution arises in relation to the number of impulses.
  The attainable absolute accuracy is frequently clearly worse and is determined by the reference switch as well as by the play of all mechanical components.

APPENDIX 5.

FUG POWER SUPPLY NTN 300-60 DATASHEET

Low voltage power supplies
Serie NTN 60 V - 300 W

Voltage: 0-60 V

Current: 0-5 A

Width: 19" / 443 mm

Height: 3 HU / 133mm

Depth: 350 mm

Weigth: 13 kg

Function

Series regulated with a set of parallel transistors and a preregulation with phase controlled thyristors. The power lost on the transistors is kept as low as possible.

Features

• High efficiency

• Short circuit proof and unlimited operation with full current in short circuit condition

• Voltage and current regulation with automatic and sharp transition

• Control mode indicated by LED

• Voltage and current setting with 10-turn potentiometers with precision scale; the adjusting knob can be locked

• 31/2 digit DVM for voltage and current (at 1/219" units, switch selected)

• Sensor terminals for the compensation of voltage drop on the load lines. The nominal voltage always refers to the output terminals

• Parallel and series connection possible

• Suitable for inductive and capacitive loads

• Standard starting current limitation from 700 W nominal power on

Design

• Up to 140 W nominal power 1/219" table-top case,

For 350 W nominal power or higher 19" table-top case

• 19" rack-adapters.

For 7 kW nominal power or higher 19" rack. Height depending on type. The side walls can be removed, the rear door can be locked.

• All cabinets have removable crane-eyes.

• Racks are equipped with castors.

• Racks 37 HU are also equipped for fork lift transport.

• Cooling: Convection or built-in fan with air outlet on the rear or the top, (depending on type).

Outputs

• 4 mm safety connectors, up to 20 A on the front panel. For higher currents, the output is on the rear. Up to 300 A - clamps, for higher currents – copper bars.

Technical Data

• Mains connection: Up to 1400 W nominal power 230 V ±10% 47 Hz to 53 Hz

• Ambient temperature: 0°C to +40°C

• Output isolation: The output is floating.

Operating voltage with respect to earth: ±500 V, either the positive or the negative terminal may be connected to earth.

All further data apply, if not otherwise stated, for voltage and current regulation and refer to the rated value.

• Setting range: from appr. 0,1% to 100%

• Setting resolution: ±1 x 10-4

• Reproducibility: ±1 x 10-3

• Residual ripple: <1 x 10-4pp + 10 mVpp

• Deviation: for ±10% mains voltage

variation: <±1 x 10-5

for no load / full load: <±2 x 10-4

over 8 hours under constant conditions: <±1 x 10-4

within the temperature range: <±1 x 10-4 /K

• Recovery time for voltage control: <50 µs for load changes from 10% to 100% or from 100% to 10%.

• Recovery time for current control: <50 ms for load changes causing an output voltage change of less than 10% of the rated voltage.

Units with an output voltage > 65 V switch off for a short time at higher load changes.

• Setting time at nominal load: 100 ms to 500 ms (depending on type) for changes of the output voltage from 10% to 90% or 90% to 10%.

• Discharging time constant for output without load: appr. 2 sec to 60 sec (depending on type).

Options

• Analog programming

• Analog programming, floating

• IEEE 488 / RS232 interface

• DVM with higher resolution

• Higher stability

• Units with 2800 W and 4200 W are also available for threephase connection.

• Water cooling

APPENDIX 6.

INTEGRATOR AT680-2030-050 DATASHEET

SPECIFICATIONS FOR VMEbus INTEGRATOR AT 680-2030-050

INPUT

input impedance: 1000 MOhm unbalanced, 2 MOhm balanced
input voltage range: +/- 5V divided by selected preamplifier gain
input resolution: 20uV divided by selected preamplifier gain with 500 kHz VFC
input protection: +/- 50V d.c. +/- 200V for 10ms

GAIN

Gain selection: 1,10,100 selected by straps using the AD524 preamplifier
1,100,200 selected by straps using the AD624 preamplifier
Other gains can be selected by installing a precision resistor

Gain non-linearity: +/- 40 ppm max. of F.S.

Gain stability: 9 ppm/deg. max. of F.S.

OFFSET

Input offset drift vs. temp, **G=1:** 10uV/deg. max.
G=10: 1uV/deg. max.
G=100: 0.25uV/deg. max.

Offset adjustment: potentiometers on front panel or with external voltage

TRIGGER

- VMEbus
- external via opto-coupler input
- incremental encoder with number of steps between triggers programmable
- internal one second time base (accuracy 15 ppm)
- output on front panel

VMEbus interface

- A16, D08 (o)

POWER SUPPLIES

- +5V/1.4A
- +12V/10mA

VMEbus integrator encoder interface jumpers and connections

Looking at the front of the encoder, if the first measurement is done in the CLOCKWISE direction, then the encoder channel Ua2 (B) should be used. This means that the following jumpers should be installed :

CHB
ENB
SWB
CMOS
I1
POL V

If, on the other hand, the first measurement is done in the ANTICLOCKWISE direction, then encoder channel Ua1 (A) should be used. This means that the following jumpers should be installed :

CHA
ENA
SWA
CMOS
I1
POL V

The above information assumes that the encoder being used has the same configuration as the Heidenhain series ROD424 and that the integrator card has been programmed as follows:

first measurement direction – rising edge encoder trigger
return measurement direction – falling edge encoder trigger

Summary

CHA, ENA, SWA:	installed if encoder channel Ua1 (A) is used
CHB, ENB, SWB:	installed if encoder channel Ua2 (B) is used
I1, POLV, CMOS:	always installed
POLA, POLB, POLI:	never installed
SW1: 5V or 12V	select the encoder supply voltage

D-Sub 9 F	Function
1	encoder channel A (Ua1)
2	not used
3	encoder channel B (Ua2)
4	not used
5	encoder index (Ua0)
6	Vcc, 5 or 12 volts
7	not used
8	ground (0 volts)
9	ground (0 volts)

Encoder interface connections

VME INTEGRATOR REGISTERS

PSR (Port Status Register)

Read

Lsb S0 Over-range (latched). Set to 1 if over-range has occurred.
S1 Not used.
S2 Encoder count validated (latched). Set to 1 if the encoder zero and the encoder-derived trigger coincide.
S3 Not used.
S4 Over-range (instantaneous). 0 if in over-range.
S5 Trigger. 0 if trigger occurred. Reset by reading 8 bytes from PADR.
S6 Not used.
msb S7 Indicates which 32 bit counter is in operation.

Write

hex 01: to reset over-range latch.
hex 04: to reset validated latch.

PADR (Port A data register)

Read

Read 8 bytes of counter data: 4 bytes for *VFC* value and 4 bytes for *offset* value.

Order: *VFC* (lsb -> msb), then *offset* (lsb -> msb). (2 x 32 bit binary values) Integrator result (Vs) = (*VFC* - (*offset*/4)) / gain_factor. See "Gain - VFC jumper positions" for the values of gain_factor.

Write

Write any value to perform a VME trigger, when this kind of trigger is selected.

PBDR (Port B data register)

Read

PB3 to PB7 define the VFC and gain configuration. See also "Gain - VFC jumper positions"

Write

PB0 and PB1 are used to select the trigger type as follows:

00: Encoder trigger.
01: External trigger.
10: Internal one second time base trigger.
11: VME trigger.

To perform a VME trigger, a write to PADR should be performed, with the VME trigger selected.

CPRH,CPRM,CPRL (Counter preload registers high, middle, low)

Read/write

Counter preload high (msb), middle and low (lsb). This is the number of encoder pulses –1 between integrator triggers and is a 24 bit binary value. When using the encoder trigger, the PI/T timer should be enabled in the TCR register, and the counter input enabled in the PCDR register. Otherwise, these two should be disabled. See also "Definitions for the 68230 PI/T chip .....".

PARR (Port A alternate register)
PBAR (Port B alternate register)

Write to these registers to select the rising or falling edges of the encoder outputs to trigger the integrator.

These signals were previously used on the first series of integrators to select the polarity of the reference output voltage:

write to PAAR to select a rising edge trigger (negative polarity on old integrators)

write to PBAR to select a falling edge trigger (positive polarity on old integrators)

VMEbus integrator triggers

The integrator has four programmable trigger sources which are selected by writing the appropriate code to the PBDR (Port B data register).

encoder trigger(00): This is derived from the incremental encoder input, via a 24 bit programmable counter. This counter is programmed with the number of encoder counts between triggers, e.g. 16 for a 256 point measurement using a 4096 pulses/turn encoder. The measurement starts when the first encoder index (zero) pulse is received. A validate signal is provided to ensure that the last integrator trigger occurred at the same time as the second encoder index pulse, meaning that no counts have been lost.
Incremental encoders similar to the one shown on the Heidenhain data sheet, Fig 1, can be used. They have two rectangular signal outputs, out of phase by 90 degrees (Ua1, Ua2) and one index or zero signal (Ua0). The encoder supply voltage can be set to 5 or 12 volts on the integrator card. For safety, it is set to 5 volts at test !

external trigger(01): This is an opto-coupler input which can be either active or passive. Interrupting the input diode current (10mA at 5v) causes a trigger. This input can be directly connected to the trigger output of another VMEbus integrator. The propagation delay is < 1 us.

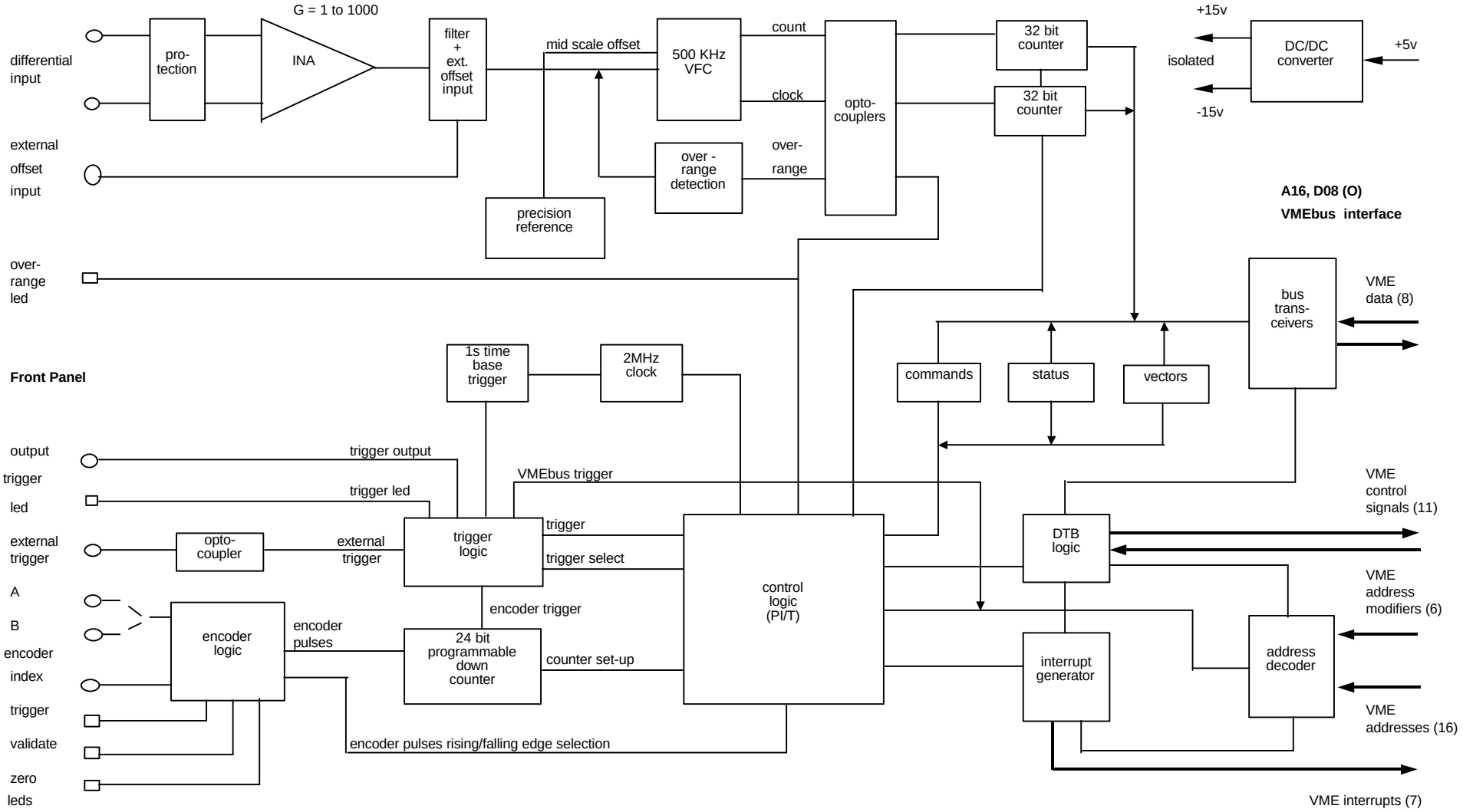
internal time base(10): This provides a precise one second measurement period which is used during calibration and for offset adjustment. It is derived from a crystal oscillator and has an accuracy of 15 ppm.

VMEbus trigger(11): This trigger is generated by writing to the address PADR (Port A data register) on the integrator card.

Offset from base address (hexadecimal)	Name	Access	Explanation	Write value (hexadecimal)
1	PGCR	R/W	Port general control register. Chip reset and register configuration byte.	00 reset,then 30
3	PSRR	R/W	Port service request register. Interrupt set-up register.	19
5	PADDR	R/W	Port A data direction register. All bits are inputs to read the 32 bit counters.	00
7	PBDDR	R/W	Port B data direction register. PB0 and PB1 are outputs to select trigger type. The rest are inputs. See table.	03
9	PCDDR	R/W	Port C data direction register. PC0 is output to enable/disable the encoder. The rest are inputs or control bits.	01
B	PIVR	R/W	Port interrupt vector register. Used to initialize the vector base number.	
D	PACR	R/W	Port A control register. Mode of operation for reg. A. Submode 1x selected.	80; 84 if interrupt
F	PBCR	R/W	Port B control register. Mode of operation for reg. B. Submode 1x selected.	80
11	PADR	R/W	Port A data register. Read 8 bytes - 4 for VFC 32 bit counter and 4 for offset counter. Order: VFC (lsb -> msb), Offset (lsb -> msb)	See table
13	PBDR	R/W	Port B data register. Write PB0, PB1 to select trigger type. Read PB2 to PB7. PB3 to PB7 define the VFC and gain configuration.	See table
15	PAAR	R/W	Port A alternate register. Write to select positive/negative rising edge encoder trigger, depending on which channel in use.	See separate sheet
17	PBAR	R/W	Port B alternate register. Write to select positive/negative rising edge encoder trigger, depending on which channel in use.	See separate sheet
19	PCDR	R/W	Port C data register. Bit 0 used to enable/disable the encoder input.	00
1B	PSR	R/W	Port status register. Used to read and reset integrator status: triggered,over-range,validation,counter position.	See table
1D	null		Not used.	
1F	null		Not used.	
21	TCR	R/W	Timer control register. Disable/enable the counter when using the encoder trigger.	E6
23	TIVR	R/W	Timer interrupt vector register. Not used.	
25	null		Not used.	
27	CPRH	R/W	Counter preload register high. Number of encoder pulses between integrator triggers (24 bits) - m.s. byte.	
29	CPRM	R/W	Counter preload register middle.	
2B	CPRL	R/W	Counter preload register low. L.s. byte.	
2D	null		Not used.	
2F	CNTRH	R	Counter register high. Not used.	
31	CNTRM	R	Counter register middle. Not used.	
33	CNTRL	R	Counter register low. Not used.	
35	TSR	R/W	Timer status register. Used to reset the zero detect bit (ZDS) when using the encoder trigger.	01

Note: See 68230 data sheet for complete programming and operational details.

Definitions for the 68230 PI/T chip used in the VME integrator AT 680-2030-050



BLOCK DIAGRAM - VMEbus INTEGRATOR

GAIN - VFC JUMPER POSITIONS and GAIN FACTOR

For VME INTEGRATOR LHC 680-2030-050

		o = jumper installed					
VFC FREQUENCY	**GAIN**	**PB7**	**PB6**	**PB5**	**PB4**	**PB3**	**Gain_factor**
500kHz	0.5	**o**	**o**				25000
500kHz	1	**o**		**o**	**o**	**o**	50000
500kHz	2	**o**		**o**	**o**		100000
500kHz	5	**o**		**o**		**o**	250000
500kHz	10	**o**		**o**			500000
500kHz	20	**o**			**o**	**o**	1000000
500kHz	50	**o**			**o**		2500000
500kHz	100	**o**				**o**	5000000
500kHz	200	**o**					10000000
500kHz	500				**o**		25000000
500kHz	1000					**o**	50000000

Register: Port B Data Register (PBDR)

Jumpers are installed on PB3 to PB7, just below IC1.

Jumper installed = logic 0.

BIBLIOGRAPHY

[1] *http://public.web.cern.ch/public/about/aboutCERN.html*

[2] U. Amaldi et al. Consistency Checks of GUT's with LEP Data. CERN-PPE/91-190, 1991.

[3] The LHC Study Group. LHC the Large Hadron Collider - Conceptual Design Vol.II. CERN/AC/95-05, October 1995. http://lhc.web.cern.ch/lhc/general/general.htm

[4] R. Schmidt. Accelerator Physics and Technology of the LHC. CERN Yellow Report 99-01, 1998.

[5] LHC Project Document LHC-PM-MS-0005, rev 1.4, April 2002.

[6] P. Schmuser. Superconductivity. In CERN Accelerator School. Superconductivity in ParticleAccelerators, Hamburg, May 1995.

[7] L. Bottura, Manufacture and performance of the LHC main dipole final prototypes. Proceedings of EPAC 2000, Vienna, Austria.

[8] K.H. Mess et al. Superconducting Accelerator Magnets. World Scientific, 1996.

[9] F. Sonnemann. Resistive Transition and Protection of LHC Superconducting Cables andMagnets. PhD thesis, RWTH, Aachen, 2001.

[10] http://www-dapnia.cea.fr/Stcm/lhcquad/design.shtml

[11] http://quench-analysis.web.cern.ch/quench-analysis/phd-fs-html/node121.html

[12] http://ab-div-co-is.web.cern.ch/ab-div-co-is/LS/Welcome.html

[13] http://ab-div.web.cern.ch/ab-div/Groups/CO/WelcomeCO.html

[14] R. Wolf, Field Error Definitions for LHC. Version 1, AT-MA Internal Note 94-102, CERN, 1994.

[15] A. Devred, M. Traveria, Magnetic Field and Flux of Particle Accelerator Magnets in Complex Formalism, DSM/DAPNIA/STCM Internal Note CRYOMAG/94/08, CEA-Saclay, 1994.

[16] A. Devred, Complex Formalism for Two Dimensional Fields, DSM/DAPNIA/STCM

Internal Note CRYOMAG/96/01, CEA-Saclay, 1996.

[17] A. Jain, Harmonic Coils, presented at CERN Accelerator School on Measurements and Alignment of Accelerator and Detector Magnets, April 11-17, 1997, Anacapri, Italy.

[18] R. Wolf, Field Error Naming Conventions for LHC Magnets, LHC Project Document LHC-M-ES-0001.00 rev. 1.0. CERN.

[19] L. Deniau, Coils Calibration – Computation and Storage of Sensitivity Factors, MTA-IN-98-021. CERN.

[20] J. Billan Standard Analysis Procedures for Field Quality Measurement of the LHC Magnets-Part I:Harmonics. MTA-IN-97-007. CERN July 21, 1997.

[21] L. Deniau, LHC/MTA. Coil Calibration. Correction factor for rectangular windings. MTA-IN-98-026. CERN April 27, 1998.

[22] S. Bidon, J. Billan, F. Fischer, C. Sanz- New Technique of fabrication of search coil for magnetic field measurement by harmonic analysis – Internal note, May 1995

[23] http://www.cis.rit.edu/htbooks/nmr/inside.htm

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